Supplemental Material

Phasing Out a Risky Technology:

An Endgame Problem in German Nuclear Power Plants?

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Main article URL: https://behavioralpolicy.org/articles/phasing-out-a-risky-technology-an-endgame-problem-in-german-nuclear-power-plants/

Methods & Analysis

A. Frequencies of reportable events

Table S1. Frequencies of reportable events per half year by individual nuclear power plant in Germany operating between 1996 & 2006 (first phaseout decision)

Year	GKN-2	KBR	KKE	KKI-2	KKP-2	KRB-II-B	KRB-II-C	KWG	KKG	GKN-1	KKU	KKI-1	KKP-1	KWB-A	KWB-B	KKB	KKK
1996_2	0	2	1	2	5	5	5	2	5	1	7	2	3	4	3	8	6
1997_1	0	1	3	0	3	1	1	1	1	3	2	1	6	5	4	5	4
1997_2	4	7	0	0	3	0	2	4	0	1	6	5	0	6	8	5	4
1998_1	2	1	1	0	2	3	1	5	4	6	10	3	5	5	3	3	5
1998_2	0	3	3	2	4	3	2	2	1	3	5	1	2	1	9	5	5
1999_1	1	6	2	1	1	1	0	3	0	6	9	2	4	4	2	7	2
1999_2	0	4	1	1	3	2	0	1	1	3	9	4	0	4	3	4	5
2000_1	1	2	2	0	1	0	2	5	6	6	5	2	4	1	4	2	3
2000_2	1	1	2	0	2	1	0	0	2	1	2	0	1	8	1	2	4
2001_1	0	4	2	1	1	4	0	0	0	3	4	1	1	2	5	2	8
2001_2	4	2	1	1	7	1	2	2	1	4	4	2	10	4	13	5	4
2002_1	2	5	2	1	5	5	1	2	2	4	1	3	6	13	4	6	8
2002_2	2	4	4	2	5	2	4	3	3	3	9	1	4	2	7	10	6
2003_1	1	2	2	2	0	2	2	6	5	3	2	5	6	4	3	5	3
2003_2	4	5	3	1	4	3	5	2	3	2	5	2	4	8	3	3	5
2004_1	1	4	7	1	3	2	1	5	0	3	3	2	7	7	11	12	4
2004_2	4	3	4	2	2	3	6	3	0	2	3	3	2	6	7	6	7
2005_1	1	7	4	1	0	4	1	7	6	3	2	5	4	6	3	8	5
2005_2	0	4	0	1	5	5	1	5	1	2	0	2	4	4	9	18	3
2006_1	2	3	4	1	1	1	3	4	6	4	3	5	3	4	9	8	7

Note. The frequencies of reportable events were retrieved from the Federal Office for the Safety of Nuclear Waste Management (http://www.bfe.bund.de/DE/kt/ereignisse/berichte/berichte_node.html). In case of reported events, which were reported at sites with two reactors without attributing the event to a specific reactor, we randomly assigned the event to one of both reactors. When an event within one plant occurred on several separate calendar dates, we coded consistently one event for each date. Alternatively, one could also code an event with several calendar dates as a single event. We also conducted this analysis. We still observe a significant increase of reported events after the 2001 decision (with M = 2.8 five years before the 2001 decision and M = 3.8 five years after the 2001 decision).

Abbreviation list: GKN-2 = Kernkraftwerk Neckarwestheim 2; KBR = Kernkraftwerk Brokdorf; KKE = Kernkraftwerk Emsland, Lingen; KKI-2 = Kernkraftwerk Isar 2, Essenbach; KKP-2 = Kernkraftwerk Philippsburg 2; KRB-II- B = Kernkraftwerk Gundremmingen B; KRB-II- C = Kernkraftwerk Gundremmingen C; KWG = Kernkraftwerk Grohnde; KKG = Kernkraftwerk Grafenrheinfeld; GKN-1 = Kernkraftwerk Neckarwestheim 1; KKU = Kernkraftwerk Unterweser, Esenshamm; KKI-1 = Kernkraftwerk Isar 1, Essenbach; KKP-1 = Kernkraftwerk Philippsburg 1; KWB-A = Kernkraftwerk Biblis A; KWB-B = Kernkraftwerk Biblis B; KKB = Kernkraftwerk Brunsbüttel; KKK = Kernkraftwerk Krümmel

Table S2. Frequencies of reportable events per half year by individual nuclear power plant in Germany operating between 2006 & 2016 (second phaseout decision)

Year	GKN-2	KBR	KKE	KKI-2	KKP-2	KRB-II-B	KRB-II-C	KWG
2006_2	1	5	3	1	1	5	3	1
2007_1	0	3	5	1	2	4	1	4
2007_2	0	2	4	0	1	1	3	3
2008_1	1	2	0	3	8	2	1	2
2008_2	5	1	1	2	1	1	3	3
2009_1	2	6	7	1	6	1	0	4
2009_2	2	2	2	3	2	0	3	3
2010_1	1	3	4	1	3	2	0	6
2010_2	1	1	1	0	1	1	1	4
2011_1	3	2	0	0	16	2	1	4
2011_2	4	4	2	1	5	2	2	3
2012_1	0	3	8	2	11	2	1	2
2012_2	2	2	1	0	3	2	2	0
2013_1	2	1	4	2	11	1	0	2
2013_2	5	3	1	3	6	2	0	1
2014_1	2	3	1	1	1	1	0	5
2014_2	2	4	1	4	5	0	0	2
2015_1	1	3	1	0	3	1	1	1
2015_2	3	1	1	2	2	1	2	1
2016_1	2	6	1	1	8	2	2	2

Note. The frequencies of reportable events were retrieved from the Federal Office for the Safety of Nuclear Waste Management (http://www.bfe.bund.de/DE/kt/ereignisse/berichte/berichte_node.html). In case of reported events, which were reported at sites with two reactors without attributing the event to a specific reactor, we randomly assigned the event to one of both reactors. When an event within one plant occurred on several separate calendar dates, we coded consistently one event for each date. Alternatively, one could also code an event with several calendar dates as a single event. We also conducted this analysis and still do not observe a significant increase after the 2011 decision.

Abbreviation list: GKN-2 = Kernkraftwerk Neckarwestheim 2; KBR = Kernkraftwerk Brokdorf; KKE = Kernkraftwerk Emsland, Lingen; KKI-2 = Kernkraftwerk Isar 2, Essenbach; KKP-2 = Kernkraftwerk Philippsburg 2; KRB-II- B = Kernkraftwerk Gundremmingen B; KRB-II- C = Kernkraftwerk Gundremmingen C; KWG = Kernkraftwerk Grohnde

Table S3. Total number of reported events in Sweden per reactor & year between January 1990 & May 2005

	Barsebäck 1	Barsebäck 2	Forsmark 1	Forsmark 2	Forsmark 3	Oskarshamn 1	Oskarshamn 2	Oskarshamn 3	Ringhals 1	Ringhals 2	Ringhals 3	Ringhals 4
1990	38	26	34	26	19	34	29	40	43	22	25	30
1991	41	29	39	32	16	79	49	31	38	35	40	42
1992	41	45	42	36	20	46	39	29	23	37	34	43
1993	48	42	30	33	23	11	44	26	55	21	29	26
1994	49	59	37	43	28	20	55	33	33	30	44	38
1995	32	35	23	38	20	21	46	24	44	62	35	39
1996	32	27	35	36	29	68	54	27	32	28	38	41
1997	33	33	51	28	32	58	56	18	36	33	30	62
1998	32	23	27	14	27	50	42	17	57	30	30	21
1999	24	23	11	12	15	43	30	19	31	25	20	13
2000	5	23	20	20	20	44	31	17	22	30	17	10
2001	0	30	17	16	17	36	22	11	29	27	23	11
2002	2	21	26	18	27	25	30	16	36	42	26	19
2003	4	36	26	28	31	44	16	19	45	27	44	23
2004	0	48	30	24	27	36	25	17	25	41	36	26
2005[1]	0	13	11	9	12	17	8	4	19	18	14	8

Note. Frequencies of reported incidents in Swedish nuclear reactors were provided by the Swedish Radiation Safety Authority.

[1]Frequencies of reported events until May 31, 2005 (date of permanent shutdown of Barsebäck 2).

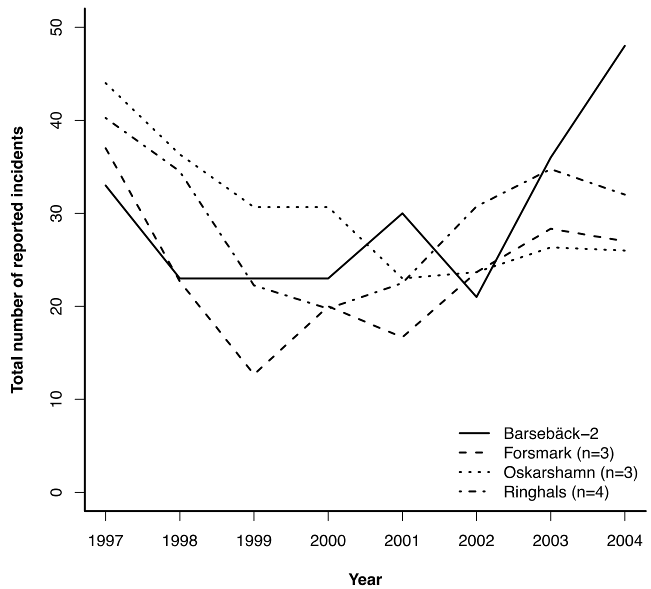

Figure S1. Frequencies of reportable events at the Swedish Barsebäck 2 reactor (which was permanently shut down in May 2005) relative to the other Swedish reactors between 1997 & 2004

The frequencies for the Forsmark, Oskarshamn, and Ringhals sites are averaged across the number of reactors (*n*) at these sites.

B. Endgame experiments

Study 1

Method

Participants

Sixty-two participants (mean age = 31.9 years; 34 females) were recruited online (via Amazon's Mechanical Turk service). Participants received 40 cents for participation and could win a bonus payment between 0 and 55 cents depending on their decisions. On average, they earned \$0.52 as an additional bonus payment. The faculty's institutional review board approved all study procedures.

Materials and Procedure

Participants were asked to act as managers of a hypothetical chemical plant and to make yes-or-no safety investment decisions for 12 management situations. Each safety investment incurred a cost of 4 points. After each decision, participants received feedback on the occurrence of accidents. If no accident occurred, they received 10 points; if an accident occurred, they lost 30 points. The initial probability of an accident was 5%. A decision not to invest in safety increased the accident probability in the next trial by 20% (for example from 5% to 6% for the first no-safety decision). A decision to invest in safety kept the accident probability in the next trial constant.

Participants were randomly assigned to two experimental between-subjects conditions, the finite and the indefinite horizon conditions. In the *finite horizon condition* (endgame condition), participants played each management situation for a fixed number of 10 periods (each period was described as a year). With 12 management situations, this resulted in a total of 120 decisions. In the *indefinite horizon condition*, the probability of each period being followed by another period (*continuation probability*) was fixed at 90%. With this continuation probability, the expected number of periods for each management situation was 10, resulting in an expected total number of 120 decisions. To make the two conditions comparable, we randomly predetermined—on the basis of the continuation probability—12 management situations with different length of periods: 2 × 15 periods, 2 × 11 periods, 2 × 5 periods, 1 × 6 periods, 1 × 14 periods, 1 × 22 periods, 1 × 2 periods, 1 × 10 periods, 1 × 4 periods. All situations together resulted in 120 decisions, as in the finite horizon condition.

Participants were informed that one of the 12 management situations would be randomly chosen at the end of the experiment and that they would be paid on the basis of the points they obtained in this situation. Participants in the indefinite horizon condition were always paid according to their points won or lost in the management situation of 10 periods in length. Because all participants could make losses or gains (depending on their performance), they started with an endowment of 1,000 points. The balance was subtracted from or added to this endowment, and the final sum was paid as an additional bonus payment (independent of the fixed payment for participation). Participants received \$0.05 for 100 points. On average, they earned \$0.52 as an additional bonus payment.

For the finite horizon condition, game theory predicts an endgame effect: The payoff-maximizing strategy is to make safety investments for the first three periods but to make no further safety investments from the fourth period on. For instance, investing in safety in all 10 periods would result in an expected payoff of 40 points. Not investing in safety in all 10 periods would result in an expected payoff of 48.08 points. Investing in the first three periods but not in the last seven periods would result in the highest expected payoff for the game of 56.17 points.

For the indefinite horizon condition, game theory predicts safety investments in each period: A continuation probability of 90% after each period results in an expected number of nine additional periods, for which the payoff-maximizing strategy is to make a safety investment.

Results

We examined participants' safety investment behavior by calculating the mean proportion of safety investments for each period averaged over the 12 management situations. Table S4 shows the mean proportion of safety investments in the two experimental conditions. To examine the effect of the endgame type, we conducted a mixed-measures ANOVA with horizon (finite versus indefinite) as a between-subjects factor and period (periods 1–10) as a within-subject factor.

Table S4. Mean proportion of safety investments (Study 1)

	Horizon conditions	
Period	Finite horizon condition (n = 31)	Indefinite horizon condition (n = 31)
1	.54 (.38)	.56 (.35)
2	.50 (.34)	.55 (.34)
3	.57 (.31)	.58 (.29)
4	.56 (.31)	.66 (.23)
5	.59 (.26)	.66 (.23)
6	.50 (.27)	.71 (.25)
7	.53 (.28)	.69 (.19)

8	.47 (.27)	.69 (.26)
9	.46 (.27)	.71 (.23)
10	.36 (.28)	.71 (.22)

Note. Standard deviations are shown in parentheses.

In general, participants in the finite horizon condition invested less frequently in safety, with an average of 50% of safety decisions, than did participants in the indefinite horizon condition, with an average of 65% of safety decisions, $F(1, 60) = 7.08$, $p = .01$, partial $\eta^2 = .11$. This main effect was qualified by a Period × Horizon interaction, $F(3.05, 183.16) = 4.74$, $p = .003$, partial $\eta^2 = .07$, indicating that investment decreased most markedly as the shutdown of the plant approached (see also Figure 2A in the main text). We further used independent *t* tests to examine the differences between the two horizon conditions per period. Applying Bonferroni correction, we found that participants in the finite horizon condition invested significantly less than did participants in the indefinite horizon condition in periods 6, 8, 9, and 10 (*p*s $< .003$). In addition, we analyzed safety investment behavior in the indefinite horizon condition in periods 11 to 22, which occurred in six of all management situations (see Figure S1).

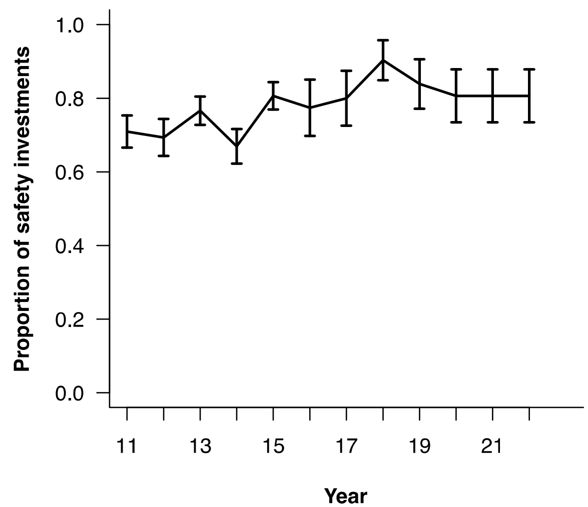

Figure S2. Proportion of safety investments by participants in the indefinite horizon condition for periods 11 to 22. Error bars represent ±1 SEM.

A repeated-measure analysis of variance (ANOVA) with period (11–22) as within-subject factor and proportion of safety investment as the dependent variable revealed no significant main effect ($p > .1$). Thus, participants' safety investments in the indefinite horizon condition remained constant from periods 11 to 22.

In summary, although participants did not strictly follow the predictions of game theory (i.e., participants in the finite horizon condition did not completely stop safety investments and participants in the indefinite horizon condition did not always invest in safety), our results showed that a finite horizon produced a declining level of safety investments, whereas an indefinite horizon resulted in a constant level of safety investment.

Study 2

Study 1 focused on strategic decisions under risk and did not involve any externalities on third parties. However, safety decisions are also likely to depend on the anticipated impact of those decisions on the health and safety of others. We therefore conducted a second study involving a social game in which each player's behavior could have negative effects on the outcomes of other players. When people follow other-regarding social preferences in a situation in which their behavior can have negative effects on the others' outcomes, they might continue to make high investments in safety, even in a finite horizon investment situation.

Furthermore, in Study 1, we used an online convenience sample of participants recruited from the Amazon Mechanical Turk (AMT) platform. Although past research has demonstrated the usefulness of this subject pool (Buhrmester, Kwang, & Gosling, 2011), there has also been criticism that individuals participate in an excessively large number of studies (Rand et al., 2014). We therefore conducted Study 2 with less-experienced participants recruited from a different online subject pool (Clickworker) and analyzed only the data of participants who correctly answered four knowledge questions about the game. Thus, Study 2 examined the robustness of Study 1's findings with a different subject population and implemented a scenario involving social externalities.

Method

Participants

We recruited 427 participants online (via Clickworker; see http://www.clickworker.com). Participants received $3.40 for participation and could win a bonus payment depending on their decisions. On average, they earned $0.51 as an additional bonus payment. Participants who registered repeatedly were excluded from further analysis (14 participants registered their worker ID twice, one participant three times, and one participant four times). Moreover, we defined two inclusion criteria: (a) participants who had participated in 20 or fewer online surveys in the last month and (b) participants who correctly answered four knowledge questions about the game. These four questions concerned the rules of the game and how payoffs were determined: (1) How many points would you get if you invested in safety and there was no accident? (2) How many points would you get if you did not invest in safety and there was no accident? (3) How many points would you lose if there was an accident? (4) How many points would you have to pay for each investment in safety? When both criteria were applied, our final sample consisted of 115 participants (mean age = 30.4 years; 47 females) with a median participation rate of one online survey in the last month. The faculty's institutional review board approved all study procedures.

Materials and Procedure

We used the same experimental paradigm and two between-subjects conditions (i.e., the finite and the indefinite horizon conditions) as in Study 1. In addition, two further between-subjects conditions (the *social-finite horizon* and the *social-indefinite horizon* conditions) were added to examine endgame effects in contexts involving externalities on third parties. These conditions were the same as the finite and indefinite horizon conditions, respectively, except that participants were told that they would be randomly and anonymously grouped into sets of four participants at the end of the experiment. If any member of the group had experienced an accident in the randomly chosen management situation, 15 points would be subtracted from the bonus of the other three group members. The maximum number of points a participant could lose was thus 45 points due to accidents experienced by the other three group members. This variant of the game does not alter the game-theoretical predictions for self-interested players: any negative effects of accidents for other players could be ignored from a selfish perspective. Furthermore, because the players did not receive any information about the behavior of the other players, it was not possible to reciprocate safety decisions of other players to build up cooperation among players, which could otherwise have promoted safety decisions in the indefinitely repeated version of the game. Thus, whereas in the indefinitely repeated version of the game, safety investments should be made in each period, in the finite version, self-interested players should make only three safety investments and then stop investing (identical to the non-social-investment game). However, if people are motivated by other-regarding preferences and not just by their own monetary outcomes, then a higher number of safety investments can be predicted in the finite version of the game. For someone with social preferences, the utility of the consequences of a decision might be determined by summing up the utility of personal payoffs and the utility due to other players' payoffs, giving both utilities equal weight. In this case, negative payoffs for other players caused by an accident would reduce the utility of a person's outcomes. It would be utility maximizing for such a participant to make six safety investments and to then stop investing in the last four periods of the game. For someone with even stronger social preferences (that is, who gives more weight to utility due to other players' payoffs than to the utility of personal payoffs), a higher number of safety investments can be predicted; for a completely altruistic person, ten safety investments are predicted).

Results

Again, we examined participants' safety investment behavior by calculating the mean proportion of safety investments for each period averaged across the 12 management situations. Table S5 shows the mean proportion of safety investments in the four experimental conditions. To examine the effect of endgame horizon type and context type, we entered the proportion of safety investments into a mixed-measures ANOVA with horizon (finite versus indefinite) and context (social versus individual) as between-subjects factors and period (period 1 to 10) as a within-subject factor.

Table S5. Mean proportion of safety investments (Study 2)

Period	Condition: Individual finite horizon (*n* = 33)	Individual indefinite horizon (*n* = 27)	Social finite horizon (*n* = 34)	Social indefinite horizon (*n* = 21)
1	.57 (.25)	.54 (.36)	.53 (.33)	.48 (.25)
2	.48 (.28)	.61 (.33)	.53 (.28)	.49 (.25)
3	.53 (.29)	.62 (.30)	.49 (.30)	.46 (.21)
4	.55 (.28)	.61 (.31)	.54 (.26)	.63 (.21)
5	.60 (.23)	.64 (.25)	.53 (.27)	.60 (.22)
6	.58 (.26)	.69 (.24)	.59 (.22)	.58 (.22)
7	.55 (.24)	.66 (.32)	.53 (.25)	.71 (.29)
8	.56 (.28)	.67 (.26)	.52 (.22)	.69 (.22)
9	.44 (.28)	.70 (.25)	.46 (.28)	.62 (.27)
10	.45 (.32)	.69 (.26)	.41 (.27)	.67 (.23)

Note. Standard deviations are shown in parentheses.

In general, participants in the finite horizon conditions invested less frequently in safety, with an average of 52% safety decisions, than did participants in the indefinite horizon conditions, with an average of 62% safety decisions, $F(1, 103) = 6.96$, $p = .01$, partial $\eta^2 = .06$. In contrast, we found no differences between the individual and social conditions and no interaction effects for context with the factors period or horizon (*p*s > .1). The main effect of the horizon was moderated by a significant Period × Horizon interaction, $F([4.30, 103) = 5.27$, $p = .001$, partial $\eta^2 = .05$, indicating decreasing investments in the finite horizon conditions as the shutdown approached (see also Figure 3B in the main text). We used independent *t* tests to examine the differences between the horizon conditions per period. Applying Bonferroni correction, we found that participants in both finite horizon conditions invested significantly less than did participants in both indefinite horizon conditions in the last three periods: 8, 9, and 10 (*p*s < .005). In addition, we analyzed safety investment behavior in the indefinite horizon conditions in periods 11 to 22, which occurred in six of the management situations (see Table S6). A repeated-measure ANOVA with period (11–22) as within-subject factor and proportion of safety investments as dependent variable revealed no significant main effect ($p > .1$). Thus, participants' safety investments in the indefinite horizon conditions remained constant from periods 11 to 22.

Table S6. Proportion of safety investments by participants in both indefinite horizon conditions for periods 11–22

Period	Individual indefinite horizon condition (*n* = 27)	Social indefinite horizon condition (*n* = 21)
11	.74 (.27)	.64 (.24)
12	.71 (.30)	.73 (.28)
13	.74 (.30)	.75 (.25)
14	.69 (.28)	.69 (.27)
15	.77 (.27)	.73 (.29)
16	.74 (.45)	.62 (.50)
17	.85 (.36)	.67 (.48)
18	.70 (.47)	.81 (.40)
19	.81 (.40)	.76 (.44)
20	.63 (.27)	.62 (.50)
21	.93 (.27)	.71 (.46)
22	.81 (.40)	.71 (46)

Note. Standard deviations are shown in parentheses.

In sum, Study 2 replicated the findings from Study 1. The results of both studies showed that a finite horizon produced a declining level of safety investments, whereas an indefinite horizon resulted in a constant level of safety investment. In addition, we observed a decline in safety investments when noninvestment decisions could have negative monetary consequences for others. Thus, the social condition did not prevent the endgame effect. Finally, as we used a different subject pool including only people with limited experience of online surveys and participants who demonstrably understood the game, these results confirm the robustness of Study 1's findings.

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