Energy Policy 129 (2019) 1339–1346

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Limits to deployment of nuclear power for decarbonization: Insights from public opinion

A. Abdulla[a], P. Vaishnav[b,*], B. Sergi[b], D.G. Victor[a,c]

[a] Center for Energy Research and Deep Decarbonization Initiative, UC San Diego, La Jolla, CA 92093, USA
[b] Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA 15213, USA
[c] School of Global Policy and Strategy and Deep Decarbonization Initiative, UC San Diego, La Jolla, CA 92093, USA

ARTICLE INFO

Keywords:
Nuclear power
Decarbonization
Risk perception
Energy modeling
Dread
Climate change

ABSTRACT

Decarbonization will require deployment of low-carbon technologies, but analysts have struggled to quantify which ones could be deployed in practice—especially where technologies have faced public opposition. For nuclear power, some analysts have tried to solve this problem with caps on deployment or nuclear-free scenarios; however, social science research has not offered nuanced guidance about these caps. We deploy an experiment involving a large U.S. sample (N = 1226) to disentangle public opposition due to the dread of nuclear power from opposition stemming from its actuarial risk. Respondents are asked to build a power generation portfolio that cuts CO_2 emissions, given information about the actuarial risks of technologies. Half the sample is exposed to the nuclear power label while the other half is treated with the risk information but blinded to the label. Respondents who see the labels deploy 6.6 percentage points less nuclear power as a share of the U.S. electricity mix. Our results suggest that dread about nuclear power leads respondents to choose 40% less nuclear generation in 2050 than they would have chosen in the absence of this dread. These methods could apply to other technologies, such as carbon storage, where there may be gaps between actuarial and perceived risks.

1. Introduction

In order to mitigate emissions of carbon dioxide and other greenhouse gases, massive investment into new energy technologies will be needed—in effect, a complete transformation of the energy system over the coming decades (International Energy Agency, 2016). One of the central results from research on transformative, deep decarbonization of the energy system is that a diverse portfolio of options will lower risks and costs (Koningstein and Fork, 2014; Edenhofer et al., 2014). Eliminating options could raise costs substantially; indeed, some research has focused on the consequences of removing nuclear power as an option (Clarke et al., 2014), because this technology in particular suffers from negative public perception in markets where it has attained its largest penetrations, such as the U.S., Western Europe, and Japan.

While public aversion to nuclear power is well-documented, the energy modeling and analyst community has struggled with how to utilize this information to assess the real-world potential for deployment of nuclear technologies. Some see these political problems as serious and prohibit new nuclear deployments altogether—often necessitating dramatic shifts to renewable energy systems or carbon capture and sequestration instead (Jacobson et al., 2015; Loftus et al., 2014). Others prohibit new investments in new nuclear power but allow existing nuclear plants to continue to operate, based perhaps on a social science theory that opponents find it easier to block permitting of new facilities while capital committed to existing plants is harder to reverse (GEA, 2012; World Wildlife Fund, 2007). Still others see concerns about climate change dominating other environmental attributes—opening a new era for base-load sources of low-carbon electricity, including nuclear power to supply bulk electricity and perhaps industrial heat with few emissions (Clarke et al., 2014; Loftus et al., 2014; Brick and Thernstrom, 2016).

In this paper, we seek to quantify what the public might allow as reasonable limits to nuclear deployment. Despite decades of analysis focused on public attitudes about nuclear power, there remains a gulf in understanding the difference between the technology's actuarial risks and the dread it evokes. Experts often emphasize actuarial risk le-

* Corresponding author.
E-mail address: parthv@cmu.edu (P. Vaishnav).

https://doi.org/10.1016/j.enpol.2019.03.039
Received 8 August 2018; Received in revised form 10 March 2019; Accepted 18 March 2019
0301-4215/

vels—for example, the often-cited claim that radiation releases from the Fukushima nuclear accident didn't kill anyone (United Nations Scientific, 2013)—with the hope that better public awareness will yield greater political support for the technology. Each new wave of designs comes with the promise that “this time will be different”—rooted in claims that advanced reactor designs are actuarially safer than current reactors (Lake et al., 2009; Moniz, 2011). In fact, the newest reactor designs are rooted in the idea of reaching the ultimate, arguably unattainable (Downer, 2014) goal of accident and sabotage-proof designs (Bullis, 2013; Strickland, 2014). None of this may matter for real world deployment, however, if the public processes risk information in ways that deviate from actuarial reality.

The purpose of our study is to quantify how much more nuclear power the public might be willing to accept if the dread associated with nuclear power were reduced or eliminated. For energy system modelers, such an exercise provides a better empirical basis than currently exists to draw conclusions about the extent to which the deployment of nuclear power is constrained by factors, such as public perception, that are not reflected in the cost. Transitions to more nuanced and realistic representations of the institutional challenges would be a boon to both modelers and policymakers. It also gives industry and other decision-makers some sense of the “size of the prize”: an estimate of how much additional nuclear power would be acceptable, if the industry invested significant effort in engaging with the public to destigmatize the technology.

We first survey the literature and identify two gaps in it that we fill with this study. We then describe our experiment, results, and implications for both energy modelers and public policy. While our focus here is on nuclear power, investigations that disentangle the root causes of public opinion could have large implications when applied to other pivotal decarbonization technologies, such as carbon capture and sequestration (CCS).

2. Our contributions to the literature

Extensive research has consistently found that the public perceives nuclear power's risks to be dramatically higher than suggested actuarially by its accident statistics. The history of research into public attitudes about nuclear power, by pollsters and psychologists, is at least four decades old (Fischhoff et al., 1978; Smith, 2001; Otway et al., 1978; Ansolabehere and Konisky, 2016). One of the earliest results suggested that the technology engenders “dread” in the public (Fischhoff et al., 1978). Since then, many studies [e.g. (Flynn et al., 1994; van der Plight, 1985; Ansolabehere and Konisky, 2009; Greenberg, 2009; Keller et al., 2012)] have sought to explain why. One hypothesis stresses how nuclear power's risks are deemed involuntary, immediate, unknown, uncontrollable, and possibly catastrophic (Fischhoff et al., 1978; Smith, 2001; Otway et al., 1978; Ansolabehere and Konisky, 2016). The role of the media in shaping these attitudes has also attracted extensive discussion [e.g. (Kemeny, 1980)]. Another oft-hypothesized cause is the relationship between ionizing radiation and cancer—a disease that, itself, often catalyzes dread. While studies have not found a general increase in the cancer-related mortality in populations residing close to nuclear power plants (Forman et al., 1987; Jablon et al., 1991), a handful of studies have observed an increased risk of childhood leukemia (National Research Council, 2012). However, no mechanism has been identified for the increased risk from radiological doses at the relevant levels. Methodological concerns have also been raised about some of the studies (Wing et al., 2011).

Public perception research has reliably found that women are more opposed to nuclear power than men (Smith, 2001; Flynn et al., 1994; van der Plight, 1985; Ansolabehere and Konisky, 2009). Recent research also shows that respondents' attitudes to nuclear power are correlated to their level of expertise in nuclear energy and in science, technology, engineering, and mathematics (STEM), with those with greater expertise displaying less negative attitudes to nuclear (Harris et al., 2018). What is new in the present paper is that we look at how such factors that are known to be important in shaping public attitudes will affect willingness to deploy nuclear power plants in the context of the fuller set of constraints and tradeoffs—such as emissions and the need to supply electricity load—that affect the overall design of the power system. Indeed, the most sophisticated public opinion research has shown that it is easy for survey respondents to express unconstrained preferences—for example, opposition to nuclear power—but more revealing when those preferences force tradeoffs (Ansolabehere and Konisky, 2016). While several studies [e.g. (Harris et al., 2018)] assess respondents' support of alternatives to nuclear, our design requires them to confront the trade-off that these choices involve: less nuclear means more renewables or more fossil fuels.

Politically left-leaning respondents also appear to be more opposed to the technology than political conservatives [e.g. (Costa-Font et al., 2008)]. At the same time, mounting concerns about global climate change have instigated a modest bifurcation in attitudes on the political left, with some still adamantly opposed to nuclear power and others accepting the technology to address a more urgent challenge: cutting emissions (Hansen et al., 2015; Monbiot, 2011). Indeed, in the United Kingdom, a coalition of reluctant acceptors has emerged over the past two decades. This coalition becomes especially strong when climate change is salient and fossil fuel prices are high (Bickerstaff et al., 2008). Still other research suggests that the problem is one of lack of trust in “risk communicators,” namely the industry and nuclear experts (Poortinga and Pidgeon, 2003; Siegrist et al., 2000). Also plausibly important is the deterioration of trust in institutions, including organized professional science, which mediates attitudes about whether regulators, firms, and experts should be allowed to manage risks (Dalton, 2005; Putnam, 2000; Gauchat, 2012; Whitfield et al., 2009). This deterioration in trust is not universal, however, and there is evidence that it is affected by identity, location, and proximity to nuclear power (Venables et al., 2012; Teräväinen et al., 2011; Corner et al., 2011).

Recent research also shows that perceived knowledge, benefits, and engagement are positively correlated with public acceptance of nuclear (Wang et al., 2019). Moreover, the willingness to accept nuclear power falls significantly after a nuclear accident, such as the Fukushima disaster of 2011: the perception of risk from the technology spiked immediately after the accident and took years to diminish (Huang et al., 2018).

In this paper, we contribute to two literatures. The **first** is the strand of literature that seeks to disentangle explanations of the low levels of public acceptance of nuclear power. The existing literature points to several interwoven explanations for low levels of public acceptance. One interprets public attitudes as largely immutable and rooted in deeper forces that lead people to brand the technology unsafe in any form. Based on this first explanation, the distaste for nuclear power is motivated primarily by the dread that it evokes, no matter how rare accidents are and regardless of their actual consequences (Slovic et al., 1981). The literature has explored the role of affect in great detail for this and other technologies (Leiserowitz, 2006; Bruine de Bruin and Wong-Parodi, 2014). Another explanation yields evaluations rooted in actuarial risk—calamitous accidents are contingencies that can be weighed with other attributes of the technology. The public, according to this view, will adjust views in response to information about benefits, such as their low emissions of greenhouse gases (Monbiot, 2011), or their enhanced safety. For instance, to reassure the public, designers of new reactors frequently tout their lower core damage risks [e.g. (Bailey, 2018)], which are rooted in estimations of the likelihood of a severe accident damaging the nuclear fuel within the core (Office of Nuclear Regulatory Research, 2016). This explanation arguably appeals to a version of the "engineer's myth" (Victor, 2011)—that, for any problem associated with any technology, there are technical modifications that would alter the risk calculation and fundamentally change public attitudes to its deployment.

We offer an experiment that separates the public's aversion to nuclear power into these two distinct components: a dread component that is not amenable to the technological interventions described above and an actuarial risk that can be reduced through better engineering solutions and public communication. To our knowledge, no prior research has sought to disentangle these two explanations in clean experiments. One study—conducted on a sample of residents in the Dutch city of Utrecht—explored the effect of labels on support for energy technologies, including nuclear (van Rijnsoever et al., 2015). However, that study co-mingled information about the catastrophic nature of nuclear accidents and information about its potential role in mitigating climate change. While experimental, it primed respondents to focus on concerns related to the security of natural gas supply (a salient European concern in 2010–12, when the study was conducted, because conflicts in Ukraine had repeatedly threatened to curtail supplies) and the high cost and land requirements of renewable energy. The study finds that labels matter, but it is impossible to determine whether that effect is the result of real shifts in attitudes or an artifact of protocol design. Our study explicitly separates dread risk, actuarial risk, and emissions; moreover, it does not prime respondents, thus allowing for a much cleaner interpretation of the experimental result.

Another study evaluated the difference in risk perception between solar power and nuclear power by formulating scenarios suggesting that annual generation from either of these technologies would lead to two or three fatalities per year (Siegrist and Sütterlin, 2014). These online studies, which were conducted on a convenience sample of residents (N = 163 and N = 302) in German-speaking Switzerland, found that the same number of fatalities evoked a far less negative response if they were associated with solar power than with nuclear power. An identical risk is considered more acceptable if it stems from solar power plants than if it stems from nuclear power plants. While this study demonstrates the influence of the "label-affect heuristic", it does not explicitly account for the fact that one of the things that worries people about nuclear is that a single accident could kill a large number of people, nor does it identify the salience of this issue or its implications.

The **second** strand of literature to which this paper contributes is the nascent effort to incorporate insights from the social sciences into energy system models. Most of these models optimize the global energy system for least-cost or least-emissions solutions. When it comes to the social acceptance of energy technologies, these models typically adopt exogenous choices—for example, some of these modeling exercises begin with a premise that excludes certain technologies (Jacobson et al., 2015). Others, such as the models used in assessment reports prepared by the Intergovernmental Panel on Climate Change (IPCC), simulate a wide range of scenarios that excludes different technologies (Clarke et al., 2014). For example, the Global Energy Assessment (GEA) Scenarios, which are widely cited in the report of Working Group III (WGIII) of the IPCC, include "No nuclear" and "No nuclear + CCS" scenarios (GEA, 2012). Table SPM.2 of the Summary for Policymakers of the WGIII report describes the additional costs of a "Nuclear phase-out" scenario, which assumes "No addition of nuclear power plants beyond those under construction, and operation of existing plants until the end of their lifetime" (Edenhofer et al., 2014). While it does not advocate excluding nuclear, Chapter 2 of Working Group III's report explicitly envisages a scenario in which an analyst, wishing to account for uncertainty, might develop a scenario that fully excludes nuclear: "An example of this would be optimal investment in energy technologies that a social planner should undertake, knowing that there might be a nuclear power ban in the near future."

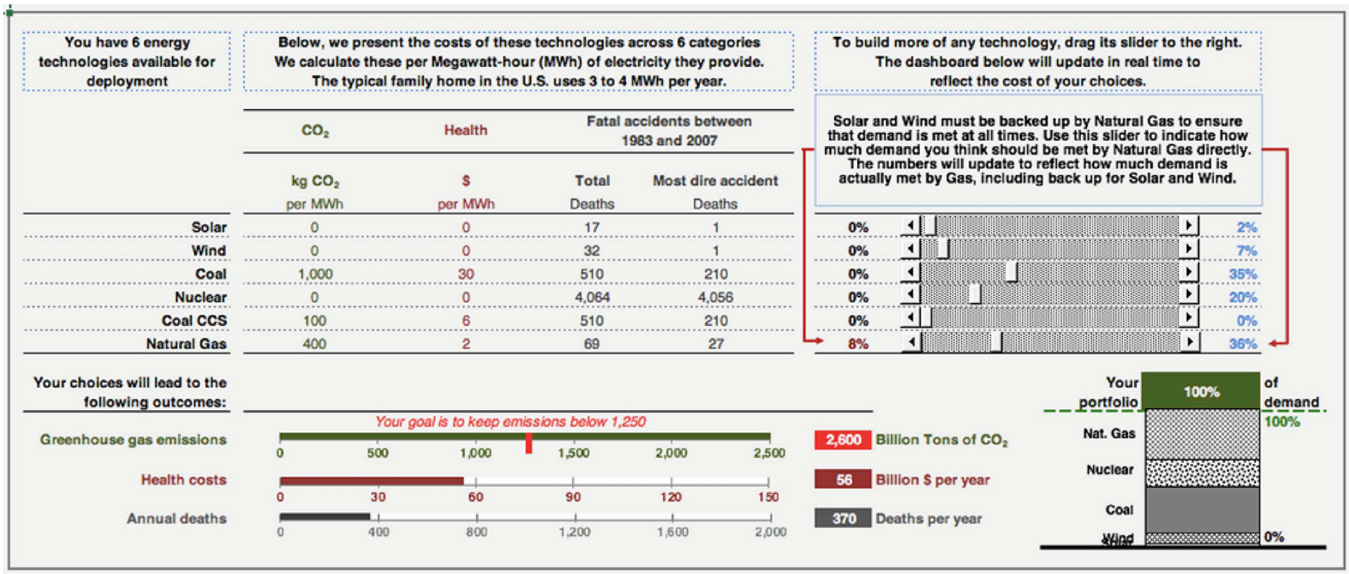
In recent years, a small but growing literature has emerged to better represent socioeconomic reality in energy modeling. One paper, for example, explored the role of state institutions in influencing investment risk and the cost of financing low-carbon energy technologies (Iyer et al., 2015). A more recent paper sought to integrate a social model of behavioral change with a climate model to outline how human perceptions of extreme events might influence greenhouse gas emissions and, ultimately, climate change (Beckage et al., 2018).

3. Methods: building a clean electricity portfolio for the U.S.

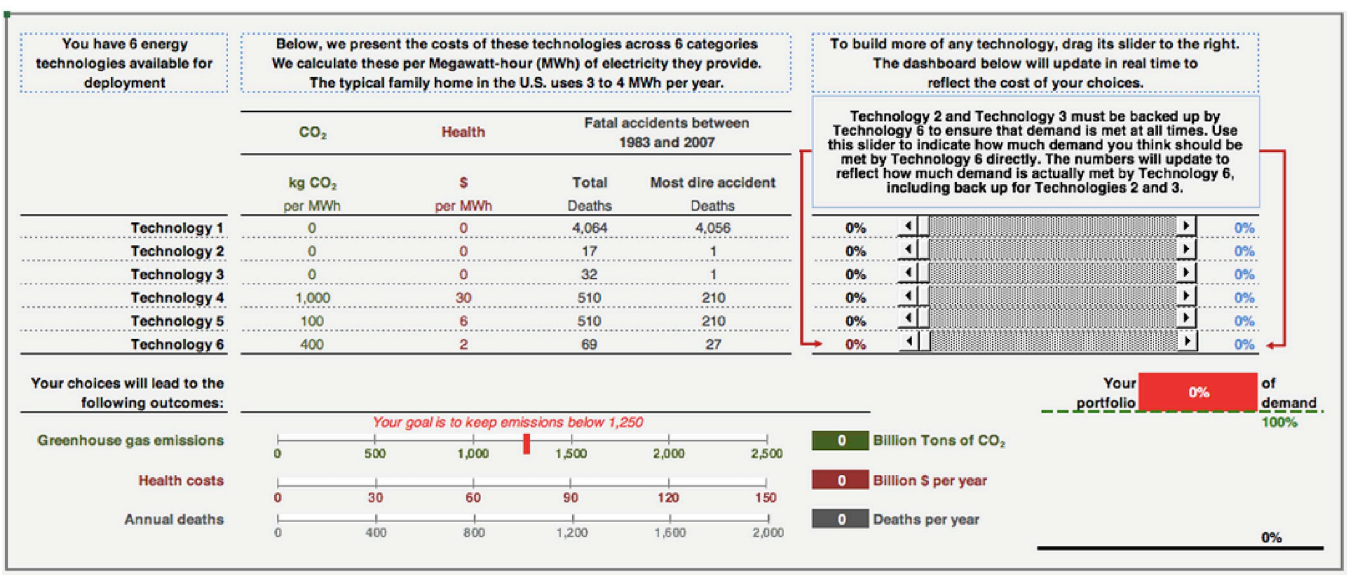
We designed a survey instrument that allowed respondents to build an electricity portfolio for the U.S. in the year 2050. We recruited respondents through Amazon Mechanical Turk (MTurk). Although it provides a convenience sample, MTurk is widely used in social science research, and researchers have found that it "can be used to obtain high-quality data inexpensively and rapidly" (Buhrmester et al., 2011) and produce results that are identical to those obtained by traditional methods of data collection such as interviews (Clifford et al., 2015). We restricted our sample to U.S. respondents by adding this screen as an MTurk qualification. Details are fully described in the supplementary materials.

Other studies, focused on very different questions, have adopted similar portfolio-building approaches to investigating public attitudes to clean energy technologies (Fleishman et al., 2010; Bessette et al., 2014). We apply one experimental treatment to our large population of respondents (N = 1226): for half the population we revealed the names of the technologies along with their actuarial risk characteristics and emissions profiles. For the other half we sequestered the names, forcing respondents to build their portfolio based just on the actuarial risk characteristics and emissions profiles of the technologies. An extensive discussion of the sources behind our calculations of both actuarial risks and emissions is included in the supplementary materials.

We included six technologies in our survey instrument (shown in Fig. 1)—wind, solar, nuclear, coal, coal with CCS, and natural gas—that represent a wide range of emissions and risk characteristics. Five are proven, scalable options for electricity generation and the sixth (coal with CCS) is widely discussed as a major future option, already incorporated into major modeling and policy efforts to reduce emissions (Clarke et al., 2014; Oxburgh et al., 2016; GEA, 2012), and attracting some modest investment. We required respondents to achieve two goals. First, they had to meet 100% of U.S. electric demand. (In practice, we accepted all responses that satisfied between 85% and 115% of demand—so that we elicited information from as large a sample as possible while not selecting out respondents who would become annoyed by a stickler survey tool.) Second, respondents had to cut power sector emissions by 50%—a cut we chose because it was broadly consistent with widely discussed near-term (2030–2050) decarbonization goals [e.g. (Senate, 2015; Public Service Commission, 2016; Turner et al., 2017; Deep Decarbonization Pathways, 2015)]. Moreover, cuts of this magnitude are deep enough that they cannot simply be satisfied by replacing coal with natural gas, a process already under way in the U.S. electric power market (Feng et al., 2015). Details regarding the survey instrument's design, the data displayed within it, and our efforts at controlling for various anchoring effects can be found in the supplementary materials but are summarized in Table 1.



(a)



(b)

Fig. 1. Two versions of the survey instrument asking respondents to build a clean electricity portfolio for the U.S. in the year 2050. **(a)** Here, technology names are exposed, the sliders are initialized to the current U.S. electric mix, and nuclear power occupies the fourth position in the list of technologies. **(b)** In this version, technology names are withheld, the sliders are initialized to zero, and nuclear power occupies the first position in the list.

Table 1
Data used in our survey instrument.

Technology	Capacity factor (%)	Lifecycle CO_2eq emissions *(tons/TWh)*	Damages from air pollution *(2007 $/kWh)*	Deaths from accidents *(Deaths/TWh)*	Total deaths	Deaths in most dire accident
Nuclear	92	~10	0	0.02	4064	4056
Wind	33	~10	0	0.44	32	1
Solar	26	~50	0	0.15	17	1
Coal	55	~1000	0.030	0.12	510	210
Coal CCS	55	~100	0.006	0.12	510	210
Natural gas	56	~500	0.002	0.02	69	27

To contend with the variability and intermittency of solar and wind generation, we configured the tool to complement each (1) unit of solar or wind generation capacity deployed by our respondents with one (1) unit of natural gas generation capacity, which is assumed to run at the same weighted average load factor (~30%) as other natural gas generating capacity in the U.S. (Energy Information Administration, 2017)

Table 2
Effect of different factors on the proportion of nuclear power in participants' portfolios, as determined by bootstrapping an ordinary least squares OLS model (n = 1226).

Variable	Without interactions		With interactions	
	Coefficient	p-value	Coefficient	p-value
(Intercept)	17.9	< 0.01	18.1	0.01
Anchor	2.2	0.14	2.0	0.18
Blind	**6.6**	**0.01**	**6.0**	**0.03**
Blind x October batch			*−0.6*	*0.45*
Blind x December batch			*3.2*	*0.28*
Blind x April replications			*0.0*	*0.49*
October batch	−3.8	0.19	−3.8	0.22
December batch	−4.6	0.11	−6.4	0.07
April replication	0.8	0.35	0.8	0.38
position 2	−0.5	0.43	−0.5	0.43
position 3	0.6	0.43	0.5	0.44
position 4	2.3	0.22	2.3	0.22
position 5	−2.0	0.24	−2.0	0.24
position 6	2.4	0.21	2.3	0.22
NEP score	0.1	0.27	0.1	0.26
Male	**9.8**	**< 0.01**	**9.8**	**< 0.01**
Partisan scale	0.7	0.13	0.6	0.12

Anchor is a dummy variable that takes the value of 1 if the version of the survey instrument presented to the respondent was anchored to the current U.S. portfolio; ***October batch***, ***December batch***, and ***April replication*** are dummy variables that take the value of 1 if the respondent was surveyed during the October 2016, December 2016, and April 2017 runs of our survey, respectively; ***position X*** are dummy variables, which take the value of 1 if nuclear power was in the "X"th position in the version of the survey instrument that was presented to the respondent; ***NEP Score*** is the score of the respondent on the New Ecological Paradigm scale (NEP, a lower score indicates greater sympathy to pro-ecological attitudes); ***Male*** is a dummy variable, which takes the value of 1 if the respondent is male; ***Partisan scale*** is a measure of how respondents self-identify on a six-point Likert scale that goes from 1 (very liberal) to 7 (very conservative). Coefficients with a p-value < 0.05 are **bold**.

We chose natural gas over electricity storage because natural gas can be deployed at scale today (Katzenstein and Apt, 2009a,b), because the use of gas in this mode is still consistent with the goal of a 50% cut in emissions, and because the analytical task would become unmanageably complex for non-experts if massive storage deployments were also introduced. Moreover, both historically (Verdolini et al., 2016) and in scenarios that model high renewables penetration, it is clear that the requirement for backup generation hovers around 1:1 in all but the extreme cases (with gas replacing coal and biomass, then replacing the former in the highest renewables scenarios) (Katzenstein and Apt, 2009a,b; Hand et al., 2012).

We bootstrapped a regression model (described in greater detail in the supplementary materials) by randomly selecting, with replacement, a synthetic sample of the same size as our full sample (i.e., N = 1226). We performed an ordinary least squares regression on this sample. This process was repeated 10,000 times, and the median values of the coefficients are reported as the effects. A "p-value" is estimated by calculating the proportion of runs in which the sign of the effect is different from the median value. The purpose of this regression was to evaluate the effect of blinding participants while controlling for other factors that might have influenced their decision (e.g., the position in which nuclear power appeared, or whether the survey instrument was anchored to the current U.S. portfolio). A bootstrapping approach was used because it is non-parametric and does not require assumptions about the distributions of any variables.

4. Results

Our results suggest that stripping nuclear power of its label—but not of actuarial information about the catastrophic nature of the risk it poses—results in a large and statistically significant increase in the technology's deployment (Table 2 and Fig. 3). Respondents who were administered the blind survey instrument opted to have nuclear power serve a 6.6% (90% CI: 3.5%–9.7%, $p < 0.01$) larger share of total U.S. electric load than those for whom technology labels were exposed. The effect of 6.6% on real-world investment is large: we used the U.S. Energy Information Administration's Annual Energy Outlook, 2016 Reference Case to calculate the amount of electricity generation in the U.S. in 2050, which is approximately 4910 TWh (Energy Information Administration, 2016). The 6.6% share translates to 324 TWh of additional nuclear generation. Since each 1000 MW_e light water reactor produces approximately 8 TWh at the average 92% U.S. reactor fleet capacity factor (Energy Information

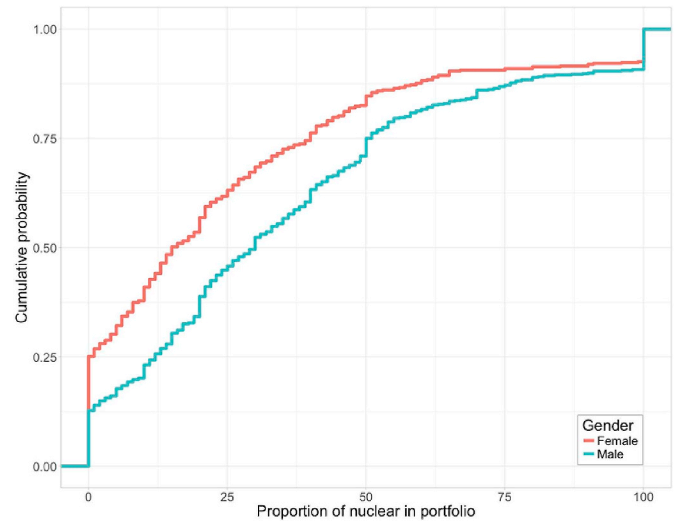


Fig. 2. Cumulative distribution functions (CDF) of the proportion of nuclear power in respondents' portfolios. The results display stochastic dominance: the CDF for male respondents is always below that of female respondents.

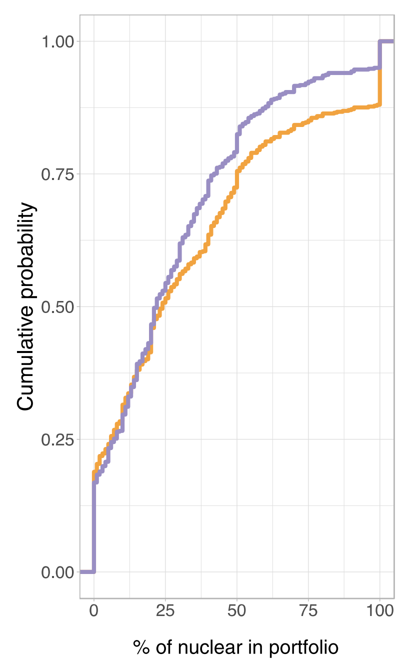


Fig. 3. Cumulative distribution functions (CDFs) of the proportion of nuclear power in respondents' portfolios in the blinded and un-blinded conditions. Roughly 50% of the respondents chose an electricity generation portfolio that was more than 25% nuclear. For this group, we see stochastic dominance: in any portfolio where the proportion of nuclear exceeds 25%, the respondent is more likely to have been blinded than not.

Administration, 2018), the additional generation derived from nuclear reactors is equivalent to adding 40 large reactors to the U.S. fleet. Unlike in earlier studies, environmental attitudes do not explain differences in preference for nuclear power. We ran our experiment multiple times, with a total of 711 respondents in October 2016 and December 2016, and a further 515 respondents in April 2017. By introducing dummies for each of these runs and testing for interactions with our main effect, we show that our results are robust: there is no significant change in the effect from one run to the next.

Women design a portfolio that is 26% nuclear when blinded and 18% when the name of the technology is revealed. For men, the numbers are 37% and 28%, 10 percentage points higher on average (90% CI: 6.9%–13%, $p < 0.01$). Fig. 2 illustrates clearly the findings of our bootstrap regression: as reported in earlier studies, male respondents have significantly more nuclear in their portfolios than do women. However, our primary result still holds: a Kolmogorov–Smirnov (KS) test ($p = 0.001$) shows that both men ($p = 0.02$) and women ($p = 0.03$) are likely to choose significantly more nuclear power in their portfolio when blinded.

107 respondents (of whom 76 or 71% were blinded) chose an all-nuclear portfolio to meet U.S. electric demand in 2050, while 237 (of whom 126 or 53% were blinded) respondents zeroed out nuclear power's contribution. We note, and Fig. 3 illustrates, that roughly 50% of the respondents chose more than 25% nuclear in their portfolio. For these respondents (half our sample), we see stochastic dominance: in any portfolio where the proportion of nuclear exceeds 25%, the respondent is more likely to have been blinded than not.

Blinding participants reduces the penetration of other low-carbon sources by roughly 2 percentage points (90% CI: 0.6–2.9) each. For example, blinded participants choose—on average—a generation mix with 16.5% solar, whereas those who are not blinded choose 19% solar. This is a substantial amount, as it accounts for twice the share of electric generation from solar power in the U.S. and more than a third of the share from wind power (Energy Information Administration, 2017). When technology labels are exposed, participants reduce nuclear power's share of the mix and meet the emissions goal by increasing the contribution from other low-carbon sources. Since the effect of the experimental treatment—exposed versus masked labels—is largest for nuclear power and roughly equal and opposite to the sum of the effect for other low-carbon technologies, the most plausible interpretation is that attitudes toward nuclear power are driving respondents' technological choices. Blinding does not have an effect on the proportion of coal chosen, either with or without CCS. This not only shows us that our participants are paying attention to the relative merits of technologies, but also that their responses are driven by their reactions to nuclear—both of which bolster our confidence in the internal validity of our experiment and our interpretation of the findings.

In the supplementary materials, we compare the demographics of our sample with those of the general U.S. population. We note that our sample is younger, more male, and more liberal than the U.S. population. Our study shows that the gap between the share of nuclear generation acceptable to "blinded" and "unblinded" respondents is greater for women than for men. On this count, it is possible that our sample, which has a higher proportion of men that the U.S. adult population, has produced a conservative estimate of the effect of blinding. Our regression controls for political affiliation and suggests that its effect is not significant. We do not know if and in what direction the fact that our sample is unrepresentative in terms of age biases our results, since the literature on the association between age and support for nuclear power is inconclusive [e.g. (Slovic et al., 2000; Ansolabehere and Konisky, 2009; Webber, 1982)].

5. Discussion and broader implications

Wherever it has been deployed, nuclear power has encountered organized public opposition, at least in part due to the dread that the technology evokes. Proponents of the technology have often blamed this dread for nuclear power's diminishing prospects and touted the safety of nuclear power as demonstrated by its accident statistics. This study is the first to estimate the "size of the prize" were this dread to be overcome—that is, the amount of nuclear power the public might accept if they considered only actuarial risk of the technology.

Knowing the technology's deployment prospects under these two scenarios would help energy system modelers align their scenarios with real-world public attitudes about risk, which enhances the utility of these models to modelers and policy makers alike. In incorporating insights from the social sciences, the energy modeling community often restricts itself to the economics of technological performance (Victor, 2015). Researchers are now seeking to better reflect public opinion in energy scenarios [e.g. (Demski et al., 2017)], but energy modelers mostly use binary tools for representing reality—for example, by prohibiting new nuclear power and contrasting those results with full portfolio, least-cost scenarios (Clarke et al., 2014). Studies such as this allow much better calibration of scenarios that might be acceptable, and the same logic could be applied to other, potentially pivotal technologies that share different risk characteristics and perception challenges. One way in which our results might be operationalized is to take the amount of nuclear power that emerges from a purely economic optimization (which, like our label-blinded participants, ignores the stigma associated with nuclear power) and reduce it by 40% to account for the average effect of dread on public support for nuclear. Although more work is needed to understand the extent to which public acceptance constrains the adoption of nuclear power, our findings suggest that the all-or-nothing approach employed by modelers today might not properly characterize the feasibility of deploying nuclear. Our estimate of the effect of dread is derived from a current U.S. sample, and other studies are needed to understand the drivers of this effect as well as its variations over time, space, and context.

Even after accounting for the catastrophic nature of the risk of nuclear power, the role that dread plays in the opposition to nuclear power is large—without it, our sample might support a U.S. nuclear fleet about 40% larger than it currently does: this would mean 40 additional large nuclear power plants, and a share for nuclear of more than 25% of the generation mix. The loss in nuclear power's share due to this dread is offset by gains in renewables and natural gas. That said, for the energy modeling community, our work suggests that constraints to the ability to deploy nuclear power are warranted in models that seek to represent politically feasible decarbonization pathways. Our results suggest that, at least in the U.S., ascribing large roles to nuclear power, or even advocating energy futures that rely heavily on nuclear power, may not be realistic without understanding the factors that help shape public support for the technology.

A second implication of the work we present here is especially relevant for policy makers and advocates of nuclear power. Many of the strategies employed by the industry to defuse the dread seem likely to fail. The development of actuarially ever-safer reactors will not allow nuclear power to gain the level of acceptability required for substantially increased deployment, unless those developments erode the dread associated with the technology. And yet, this appears to be the industry's proposed solution to the problem (Bullis, 2013; Strickland, 2014). Although improvements to safety are important, overcoming the public's dread hinges on deliberate stakeholder engagement and two-way communication by the nuclear industry and policy makers.

Finally, while our experiment is retrospective, experiments such as this can have a prophylactic role also. If regular assessments of a technology's public risk perception reveal a widening chasm between the actuarial and perceived risks, this should trigger policy makers and industry to take corrective action before negative attitudes harden. Alternatively, such a rupture might suggest that the technology is close to the upper limit of acceptable levels of deployment. These lessons will be especially important for technologies that are so novel that public perceptions have yet to fully form (Reiner, 2015). Indeed, Michelson

(2016) points out that the Project on Emerging Nanotechnologies (PEN) conducted, and published the results of, regular public opinion surveys about nanotechnology (e.g. (Hart Research Associates, 2009)). A former PEN staffer, quoted by Michelson, notes that such regular surveys "were critical to stimulating a fresh round of conversations about nanotechnology and society on a consistent basis," and also "offered a recurring opportunity to influence the thinking of policymakers and other stakeholders" [(Michelson, 2016), pp. 90]. Similarly, the Synthetic Biology Project conducted regular public perception surveys [(Michelson, 2016), pp. 34]. Within the energy sector, examples include CCS: early evidence suggests that the public understands and fears links to human-induced earthquakes (Ashworth et al., 2015). Despite differences in risk perception among technologies, planners seek to include social aspects in power planning (Ribeiro et al., 2011). Industries should, through two-way communication, seek to understand and address the origins of the public disquiet about a technology. Both planners and industry should learn from the failure of the nuclear industry to close the long-lived gap between the actuarial and dread risks of their energy technology.

Acknowledgement

This work was supported by the UC San Diego Frontiers of Innovation Scholars Program; the UC San Diego School of Global Policy and Strategy; the Electric Power Research Institute; and the Center for Climate and Energy Decision Making at Carnegie Mellon University, which is supported by the U.S. National Science Foundation (SES-094970). We are grateful to Prof. Alex Davis of Carnegie Mellon University for his advice on designing the survey instrument and on non-parametric data analysis.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2019.03.039.

References

Ansolabehere, S., Konisky, D.M., 2009. Public attitudes towards construction of new power plants. Publ. Opin. Q. 73 (3), 566–577.
Ansolabehere, S., Konisky, D.M., 2016. Cheap and Clean: How Americans Think about Energy in the Age of Global Warming. MIT Press, Cambridge, MA, USA.
Ashworth, P., Wade, S., Reiner, D., Liang, X., 2015. Developments in public communications on CCS. Int. J. Greenh. Gas Control 40, 449–458.
Bailey, J., 2018. NuScale Power: Blazing a Trail in the United States and beyond. Nuclear Energy Insider Webinar (18 January 2018).
Beckage, B., Gross, L.J., Lacasse, K., Carr, E., Metcalf, S.S., et al., 2018. Linking models of human behavior and climate alters projected climate change. Nat. Clim. Change 8, 79–84.
Bessette, D.L., Arvai, J., Campbell-Arvai, V., 2014. Decision support framework for developing regional energy strategies. Environ. Sci. Technol. 48 (3), 1401–1408.
Bickerstaff, K., Lorenzoni, I., Pidgeon, N.F., Poortinga, W., Simmons, P., 2008. Reframing nuclear power in the UK energy debate: nuclear power, climate change mitigation and radioactive waste. Public Understand. Sci. 17 (2), 145–169.
Brick, S., Thernstrom, S., 2016. Renewables and decarbonization: studies of California, Wisconsin and Germany. Electr. J. 29, 6–12.
Bruine de Bruin, W., Wong-Parodi, G., 2014. The role of initial affective impressions in responses to educational communications: the case of carbon capture and sequestration (CCS). J. Exp. Psychol. Appl. 20 (2), 126–135.
Buhrmester, M., Kwang, T., Gosling, S.D., 2011. Amazon's Mechanical Turk: a new source of inexpensive, yet high-quality, data? Perspect. Psychol. Sci. 6, 3–5.
Bullis, K., 2013. Safer Nuclear Power, at Half the Price. MIT Technol Rev.
Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., et al., 2014. Assessing Transformation Pathways in Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge UP, Cambridge, UK and New York, NY, USA.
Clifford, S., Jewell, R.M., Waggoner, P.D., 2015. Are samples drawn from Mechanical Turk valid for research on political ideology? Res. Polit. 2 (4), 1–9.
Corner, A., Venables, D., Spence, A., Poortinga, W., Demski, C., Pidgeon, N., 2011. Nuclear power, climate change and energy security: exploring British public attitudes. Energy Policy 39 (9), 4823–4833.
Costa-Font, J., Rudisill, C., Mossialos, E., 2008. Attitudes as an expression of knowledge and "political anchoring": the case of nuclear power in the United Kingdom. Risk Anal. 28 (5), 1273–1287.
Dalton, R.J., 2005. The social transformation of trust in government. Int. Rev. Sociol. 15 (1), 133–154.
Deep Decarbonization Pathways Project, 2015. Pathways to Deep Decarbonization 2015 Report – Executive Summary. Institute for Sustainable Development and International Relations and the Sustainable Development Solutions Network 2015.
Demski, C., Spence, A., Pidgeon, N., 2017. Effects of exemplar scenarios on public preferences for energy futures using the my2050 scenario-building tool. Nat. Energy 2, 17027.
Downer, J., 2014. In the Shadow of Tomioka: On the Institutional Invisibility of Nuclear Disaster – Discussion Paper No: 76 Center for Analysis of Risk and Regulation. London School of Economics and Political Science, London, UK.
Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., et al., 2014. Summary for Policymakers in Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge UP, Cambridge, UK and New York, NY, USA.
Energy Information Administration, 2016. Annual Energy Outlook Table 8. U.S. Department of Energy, Washington, DC, USA.
Energy Information Administration, 2017. Annual Energy Outlook 2017. U.S. Department of Energy, Washington, DC, USA.
Energy Information Administration, 2018. Electric Power Monthly Table 6.7.B. U.S. Department of Energy, Washington, DC, USA.
Energy Information Administration, 2017. Net Summer Capacity of Utility Scale Units Using Primarily Fossil Fuels and by State, December 2016 and 2015 (Megawatts) – Table 6.2.C. U.S. Department of Energy, Washington, DC, USA.
Feng, K., Davis, S.J., Sun, L., Hubacek, K., 2015. Drivers of the US CO2 emissions 1997-2013. Nat. Commun. 6, 7714.
Fischhoff, B., Slovic, P., Lichtenstein, S., Read, S., Combs, B., 1978. How safe is safe enough? A psychometric study of attitudes towards technological risks and benefits. Policy Sci. 9 (2), 127–152.
Fleishman, L.A., Bruine de Bruin, W., Morgan, M.G., 2010. Informed public preferences for electricity portfolios with CCS and other low-carbon technologies. Risk Anal. 30 (9), 1399–1410.
Flynn, J., Slovic, P., Mertz, C.K., 1994. Gender, race, and perception of environmental health risks. Risk Anal. 14 (6), 1101–1108.
Forman, D., Cook-Mozaffari, P., Darby, S., Davey, G., Stratton, I., Doll, R., et al., 1987. Cancer near nuclear installations. Nature 329 (8), 499–505.
Gauchat, G., 2012. Politicization of science in the public sphere: a study of public trust in the United States, 1974-2010. Am. Sociol. Rev. 77 (2), 167–187.
GEA, 2012. Global Energy Assessment: towards a Sustainable Future. International Institute for Applied Systems Analysis and Cambridge UP, Cambridge, UK.
Greenberg, M., 2009. Energy sources, public policy, and public preferences: analysis of US national and site-specific data. Energy Policy 37 (8), 3242–3249.
National Renewable Energy Laboratory, 2012. In: In: Hand, M.M., Baldwin, S., DeMeo, E., Reilly, J.M., Mai, T., Arent, D., Porro, G., Meshek, M., Sandor, D. (Eds.), Renewable Electricity Futures Study, vol. 4 National Renewable Energy Laboratory, Golden, CO, USA NREL/TP-6A20-52409.
Hansen, J., Emanuel, K., Caldeira, K., Wigley, T., 2015. Nuclear Power Paves the Only Viable Path Forward on Climate Change. The Guardian (3 December 2015).
Harris, J., Hassall, M., Muriuki, G., Warnaar-Notschaele, C., McFarland, E., et al., 2018. The demographics of nuclear power: comparing nuclear experts', scientists' and non-science professionals' views of risks, benefits and values. Energy Res. Soc. Sci. 46, 29–39.
Hart Research Associates, 2009. Nanotechnology, Synthetic Biology, & Public Opinion. The Woodrow Wilson International Center For Scholars, Washington, DC, USA.
Huang, L., He, R., Yang, Q., Chen, J., Zhou, Y., et al., 2018. The changing risk perception towards nuclear power in China after the Fukushima nuclear accident in Japan. Energy Policy 120, 294–301.
International Energy Agency, 2016. World Energy Outlook 2016. Organization for Economic Co-operation and Development, Paris, France.
Iyer, G.C., Clarke, L.E., Edmonds, J.A., Flannery, B.P., Hultman, N.E., et al., 2015. Improved representation of investment decisions in assessments of CO_2 mitigation. Nat. Clim. Change 5, 436–440.
Jablon, S., Hrubec, Z., Boice, J.D., 1991. Cancer in populations living near nuclear facilities. J. Am. Med. Assoc. 265 (11), 1403–1408.
Jacobson, M.Z., Delucchi, M.A., Cameron, M.A., Frew, B.A., 2015. Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes. Proc. Natl. Acad. Sci. U.S.A. 112 (49), 15060–15065.
Katzenstein, W., Apt, J., 2009a. Response to comment on "air emissions due to wind and solar power". Environ. Sci. Technol. 43 (15), 6108–6109.
Katzenstein, W., Apt, J., 2009b. Air emissions due to wind and solar power. Environ. Sci. Technol. 43 (2), 253–258.
Keller, C., Visschers, V., Siegrist, M., 2012. Affective imagery and acceptance of replacing nuclear power plants. Risk Anal. 32 (3), 464–477.
Kemeny, J., 1980. Saving American democracy: the lessons of Three Mile Island. Technol. Rev. 83, 65–75.
Koningstein, R., Fork, D., 2014. Energy's creative destruction. IEEE Spectr. 51 (12), 30–35.
Lake, J.A., Bennett, R.G., Kotek, J.F., 2009. Next Generation Nuclear Power: new, safer and more economical nuclear reactors could not only satisfy many of our future energy needs but could combat global warming as well. Sci. Am. 286 (1).
Leiserowitz, A., 2006. Climate change risk perception and policy preferences: the role of affect, imagery, and values. Clim. Change 77 (1–2), 45–72.
Loftus, P.J., Cohen, A.M., Long, J.C.S., Jenkins, J.D., 2014. A critical review of global decarbonization scenarios: what do they tell us about feasibility? WIREs Clim.

Change 6, 93–112.
Michelson, E.S., 2016. Assessing the Societal Implications of Emerging Technologies: Anticipatory Governance in Practice. Routledge, London, UK.
Monbiot, G., 2011. Why Fukushima Made Me Stop Worrying and Love Nuclear Power. The Guardian (21 March 2011).
Moniz, E., 2011. Why we still need nuclear power: making clean energy safe and affordable. Foreign Aff. 90 (6), 83–94.
National Research Council, 2012. Analysis of Cancer Risks in Populations Near Nuclear Facilities: Phase I. National Academy Press, Washington, DC, USA.
Office of Nuclear Regulatory Research, 2016. Probabilistic Risk Assessment and Regulatory Decisionmaking: Some Frequently Asked Questions – NUREG-2201. U.S. Nuclear Regulatory Commission, Rockville, MD, USA.
Otway, H.J., Maurer, D., Thomas, K., 1978. Nuclear power: the question of public acceptance. Futures 10 (2), 109–118.
Oxburgh, R., et al., 2016. Lowest Cost Decarbonization For the UK: the Critical Role of CCS Parliamentary Advisory Group on Carbon Capture and Storage. (London, UK).
Poortinga, W., Pidgeon, N.F., 2003. Exploring the dimensionality of trust in risk regulation. Risk Anal. 23 (5), 961–972.
NY Public Service Commission, 2016. Order Adopting a Clean Energy Standard.
Putnam, R.D., 2000. Bowling Alone: the Collapse and Revival of American Community. Simon & Schuster, New York, NY, USA.
Reiner, D.M., 2015. Where can I go to see one? Risk communications for an 'imaginary technology'. J. Risk Res. 18 (6), 710–713.
Ribeiro, F., Ferreira, P., Araujo, M., 2011. The inclusion of social aspects in power planning. Renew. Sustain. Energy Rev. 15 (9), 4361–4369.
Senate, C.A., 2015. Senate Bill No. 350: Clean Energy and Pollution Reduction Act of 2015.
Siegrist, M., Sütterlin, B., 2014. Human and nature-caused hazards: the affect heuristic causes biased decisions. Risk Anal. 34 (8), 1482–1494.
Siegrist, M., Cvetkovich, G., Roth, C., 2000. Salient value similarity, social trust, and risk/benefit perception. Risk Anal. 20 (3), 353–362.
Slovic, P., Fischhoff, B., Lichtenstein, S., 1981. In: In: Monroe, K.B. (Ed.), Facts and Fears: Societal Perception of Risk in Advances in Consumer Research, vol. 8. pp. 497–502.
Slovic, P., James, F., Mertz, C.K., Poumadere, M., Mays, C., 2000. In: Renn, O., Rohrmann, B. (Eds.), Nuclear Power and the Public in Cross-Cultural Risk Perception: A Survey of Empirical Studies. Springer, Boston, MA, USA.
Smith, E.R.A.N., 2001. Energy, the Environment, and Public Opinion. Rowman & Littlefield, Lanham, MD, USA.
Strickland, E., 2014. Start-up: transatomic Power Wants to Build a Better Reactor: its "walk-away safe" nuclear reactor would run on spent fuel. IEEE Spectr. 51 (7), 25–26.
Teräväinen, T., Lehtonen, M., Martiskainen, M., 2011. Climate change, energy security, and risk—debating nuclear new build in Finland, France and the UK. Energy Policy 39 (6), 3434–3442.
Turner, A., et al., 2017. Better Energy, Greater Prosperity: Achievable Pathways to Low-Carbon Energy Systems. Energy Transitions Commission 2017.
United Nations Scientific Committee on the Effects of Atomic Radiation, 2013. UNSCEAR 2013 Report to the General Assembly, with Scientific Annexes. (United Nations, Vienna, Austria).
van der Plight, J., 1985. Public attitudes to nuclear energy: salience and anxiety. J. Environ. Psychol. 5 (1), 87–97.
van Rijnsoever, F.J., van Mossel, A., Broecks, K.P.F., 2015. Public acceptance of energy technologies: the effects of labeling, time, and heterogeneity in a discrete choice experiment. Renew. Sustain. Energy Rev. 45, 817–829.
Venables, D., Pidgeon, N.F., Parkhill, K.A., Henwood, K.L., Simmons, P., 2012. Living with nuclear power: sense of place, proximity, and risk perceptions in local host communities. J. Environ. Psychol. 32 (4), 371–383.
Verdolini, E., Vona, F., Popp, D., 2016. Bridging the Gap: Do Fast Reacting Fossil Technologies Facilitate Renewable Energy Diffusion? *NBER Working Paper 22454*. National Bureau of Economic Research, Cambridge, MA, USA.
Victor, D.G., 2011. Global Warming Gridlock. Cambridge UP, Cambridge, UK and New York, NY, USA.
Victor, D.G., 2015. Embed the social sciences in climate policy. Nature 520, 27–29.
Wang, S., Wang, J., Lin, S., Li, J., 2019. Public perceptions and acceptance of nuclear energy in China: the role of public knowledge, perceived benefit, perceived risk and public engagement. Energy Policy 126, 352–360.
Webber, D.J., 1982. Is nuclear power just another environmental issue? An analysis of California voters. Environ. Behav. 14 (1), 72–83.
Whitfield, S.C., Rosa, E.A., Dan, A., Dietz, T., 2009. The future of nuclear power: value orientations and risk perception. Risk Anal. 29 (3), 425–437.
Wing, S., Richardson, D.B., Hoffman, W., 2011. Cancer risks near nuclear facilities: the importance of research design and explicit study hypotheses. Environ. Health Perspect. 119 (4), 417–421.
World Wildlife Fund, 2007. Climate Solutions: WWF's Vision for 2050. World Wildlife Fund, Gland, Switzerland.