Dimming Hopes for Nuclear Power: Perceptions of Risk as Shadow Costs

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Abstract

The preferences expressed in voting on nuclear power licenses and the risk attitudes of citizens provide insights into decision-making in energy policy and impacts on social welfare. Our analysis builds upon an analytical model which shows that if people's risk perceptions affect their stand on nuclear power, biased perceptions of the probability of accidents pose a cost to society. These costs consist of disutility caused by unnecessary anxiety, due to misperceived risks of existing reactors, and where licenses for new nuclear reactors are not granted, delayed or totally lost energy production. Empirical evidence is derived from Finnish surveys eliciting explicitly the significance of risk perceptions in respondents' preferences regarding nuclear power and its environmental and economic impacts. Various model specifications show that the estimated marginal impact of a high perceived risk of nuclear accident is statistically significant and that such a perception considerably decreases the probability of a person supporting nuclear power. As biased risk perceptions may cause costs to society, ascertaining and understanding people's risk perceptions can help reduce expenditures, improve risk management and enhance social welfare.

Keywords: energy, vote, nuclear accident, subjective risks, probabilities, binary variable, instrumental variable

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1.Introduction

Nuclear power is a contentious subject in energy policy. It supplies base-load energy with low operation costs and, appealingly for the international community in tackling climate change, features production of energy without CO_2 emissions. However, nuclear power uses non-renewable uranium as an input and the technology is plagued by apprehension related to radioactivity. Because of concerns about nuclear accidents and the handling and storage of spent fuel, nuclear power has long been controversial among the public. The safety risks have typically been considered the most challenging external costs of nuclear power (Davis 2012, Kessides 2012). For these reasons, in most countries, the licensing process for nuclear power is subject to political control and, to ensure risk management, production is strictly regulated by nuclear safety authorities.

For decision makers who seek to determine safety margins for risk management, risks can be estimated by calculating objective probabilities of accidents at nuclear power plants. These probabilities are small but, interestingly, private insurance companies will not provide full-coverage insurance against accidents. This policy can most likely be attributed to the potentially vast and long-lasting damage that would follow from a large-scale catastrophe, the claims for which would lead to bankruptcy even for an alliance of insurance companies. Ultimately, in the case of an extreme emergency, clean-up and compensation to victims for damage and injury are the responsibility of government.[1]

This paper focuses on the impacts on welfare of perceived risks of a nuclear power plant accident. As the probability of a large-scale accident is very small, but the resulting damage may be enormous, the probability of an accident and the scope of the ensuing damage may become intertwined in people's reasoning and result in exaggerated perceptions of risk.[2] Therefore, it is likely that perceived risks deviate from objectively estimated probabilities and in final decisions on licenses for new nuclear reactors, for example, such perceptions may play a weightier role than estimated objective probabilities. Moreover, decisions by politicians may be influenced not only by their own risk

[1] International conventions limit the liabilities of operators of nuclear power plants so that beyond the limit the state can accept responsibility as insurer of last resort. For example, Fukushima I Nuclear Power Plant was insured for some tens of millions of euros with German Nuclear Insurance Association; yet, no insurance was provided for damage caused by earthquakes, tsunamis, and volcanic eruptions, and insurer had no liability to Tokyo Electric Power Company (clean-up costs of Fukushima have been estimated to USD 50-250 billion during the next decades).

[2] The tendency to overestimate small probabilities has been widely discussed in the context of prospect theory (Kahnemann and Tversky 1979; see also Barberis 2013).

perceptions, but also by the opinions of citizens or voters or politicians' views of their constituents' perceptions.[3]

From a social point of view, investigation of risk perceptions reveals insights into their welfare consequences, which become capitalized in political decisions in licensing processes. We show analytically that if people's risk perceptions affect their stand on nuclear power, biased perceptions of accident probabilities pose a cost to society. These costs show up in two forms: unnecessary anxiety due to misperceived or exaggerated risks of existing reactors and, where licenses for new nuclear reactors are not granted, delayed or totally lost energy production. Understanding people's risk perceptions can help reduce expenditures, delays and enmity, and improve risk management and social welfare.

We investigate how important risk perceptions are in voting on nuclear energy. We introduce a simple model for measuring the shadow costs of nuclear power resulting from perceived risks of a nuclear accident. Based on the welfare components identified in the analytical model, we measure perceived risks of nuclear accident using surveys addressed to the general public in Finland. Drawing on the survey data we can estimate how important a factor risk perceptions are for calculations of the social costs of nuclear power.

Finland is a particularly interesting country in which to study nuclear power and risk perceptions. During the past 30 years there has been a parliamentary vote on licenses for new nuclear reactors every decade, and the risks of nuclear power have been discussed in public debates in connection with each vote. Moreover, one of the world's most keenly followed and latest nuclear-reactor technologies, the European Pressurized Water Reactor (EPR), has been under construction in Finland for almost ten years. Since opinion polls regarding nuclear power in connection with each vote in Parliament and, more recently, delays in the start-up of energy production at the new nuclear reactor have frequently been reported in the media, the public is familiar with the issue of nuclear power. We investigate whether the public's risk perceptions affect their stand on nuclear power and stated behavior of voting on new licenses for nuclear reactors.

[3] See, e.g., Nelson (2002) for political decision-making in environmental issues.

Our study draws on extensive previous research on risk perceptions. There is a vast literature in cognitive psychology on risk attitudes and perceptions (e.g., Fischhoff et al.1978; Slovic 1999; Slovic et al 2004; Sjöberg 2000). Economics as well has a comprehensive literature studying the determinants of risk attitudes using data from laboratory experiments and surveys (e.g. Dohmen et al. 2011, Harrison et al. 2007, 2013). We measure perceptions of risks by responses to multiple survey items eliciting risk attitudes in the specific context of a referendum-type vote on nuclear power licenses. As we have responses to several risk questions, we can observe the use of the risk scale in separate items by every individual and control for the risk attitudes when explaining preferences in voting.[4] We study the impacts of gender, age, education and risk attitudes on voting for or against license applications for new nuclear power reactors in Finland. Our analysis of hypothetical voting bears similarities to that conducted by Kunreuther et al (1990), who analyzed attitudes toward siting a nuclear waste repository in Nevada. In our study, we are aware of a potential endogeneity bias, to which attention has been drawn in the recent literature, for example, by Baker et al (2009) in their model on subjective risks of hurricanes and intended moving and location choice, and by Riddel (2011) in her model on perceived mortality risk and acceptance of the risk of nuclear waste transport. We show that our results of the impacts of perceptions of the risk of a nuclear accident on voting are robust to a series of specification checks, including an instrumental variable estimation.

In the following, we first provide the political and social context of our study by discussing issues of nuclear power safety and reviewing the relevant literature related to risk perceptions. Thereafter, we present the simple analytical framework that underlies the statistical analysis of the voting behavior. In section 4, we briefly motivate the issues queried in the survey and describe the data collected. Section 5 presents the estimation results and section 6 discusses their policy implications. Section 7 concludes.

2. Nuclear power policy, safety and risk perceptions

As nuclear power has been associated with risks and prompted intense emotions throughout its history of civil use, it has always been a strongly polarized issue in politics. The risk perceptions capitalize into political decision-making on licensing new reactors. If there is strong opposition among the public, decision-makers are not willing to approve new licenses. This section provides background on the

[4] In fact, for a sample of the members of the Finnish parliament we observe actual voting behavior in the parliament regarding licenses and their stated risk perceptions. For details, see Aatola and Huhtala (2014).

energy policy regarding nuclear power and discusses the role which perceptions of the risk of an accident play in relation to objective risk assessment.

2.1 Energy policy regarding nuclear power and the Finnish context

Before the Fukushima accident in Japan in 2011, there was a rather widespread confidence in a “nuclear renaissance” in many countries, including the United States (e.g., Blue Ribbon Commission nominated by President Obama). After Fukushima, the reaction in energy policy to the accident was swift in Europe, particularly in Germany. Germany immediately closed down 8 GW of nuclear capacity and passed a law to phase out its remaining plants by 2022. However, most countries have decided to keep nuclear power in their energy mix (Barbi and Davide 2012). In the US, two license applications were approved by the US Nuclear Regulatory Commission in 2012. As the Swedish Parliament had decided to overturn a ban on building new nuclear reactors (in force since 1980), one of the largest utilities in the European energy industry, Vattenfall, submitted an application in 2012 to the Swedish regulator, in which it sought to replace as many as two of its existing reactors with new ones; building plans would not take effect until 2030 at the earliest. In 2013, the UK announced its intention to award a contract to a French energy company to build a new nuclear reactor. In total, there are currently about 70 nuclear reactors under construction in the world; of these, 29 are in China and 11 in Russia (IAEA 2014).

The nuclear industry has been struggling with ever-escalating construction costs (Davis 2012, Kessides 2012), and it is claimed that part of these cost increases are attributable to safety regulations.[5] Considering private costs alone, that is, not taking into account the social costs of nuclear power, the competitiveness of nuclear power is considered ”questionable” (Linares & Conchado 2013). This finding is supported by the recent decision of the UK government on guaranteeing the price for power from a nuclear plant to be built at Hinkley Point that is double the current wholesale power price; the legality of such financial support alone is under investigation by the EU (European Voice 2013).

[5] After the Three Mile Island accident, reforms were launched in emergency response planning, reactor operation training, human factors engineering, radiation protection etc. After Chernobyl, third generation reactors have been intensely developed. After 9/11, nuclear power plants must provide adequate protection in a hypothetical attack by an airplane. After Fukushima, additional new safety standards have been introduced by EU and other individual countries.

Our empirical analysis builds upon experiences in Finland. Currently, there are four nuclear reactors that have been operating since the late 1970s and early 1980s, providing about 32 % of the country's electricity. The Nuclear Energy Act, passed in 1987, prescribes the Finnish Parliament makes the final decision on nuclear reactor licenses (OECD 2008). A license for a fifth power reactor was turned down by Parliament in 1993, but accepted in 2002. Since 2005, the fifth reactor has been, and still is, under construction. The construction of the reactor was launched as a flagship project for two energy companies, Finnish TVO and French Areva, and there is world-wide interest in its third-generation EPR nuclear technology. The reactor was expected to be in operation in 2009, but the latest assessments estimate operation to start in 2016 at the earliest.[6]

Despite the heavy delays and increasing cost projections of the fifth reactor, the Finnish Parliament accepted licenses for two additional nuclear reactors in 2010 for two energy companies (TVO and Fennovoima). Risks were widely discussed in debates before the parliamentary votes. Parliament also decided to support the industry's application for constructing an extended final disposal repository for spent nuclear fuel generated in Finland. The votes in Parliament took place eight months before the accident at the Fukushima Daiichi Nuclear Plant. After the accident, the media placed safety issues higher on the agenda that they had than before.

The point of departure in our analysis is the vote on nuclear reactor licenses in Parliament in 2010. Public debate preceding the actual vote focused on meeting the Finnish targets to cut greenhouse gas emissions, the possible employment effects of the new nuclear power plants, their influence on renewable energy investments and safety issues. However, surprisingly little is known about the risk perceptions related to energy production that were debated prior to the decision of the Finnish Parliament to support an increased supply of nuclear energy.

2.2 Objective risk of accident and perceptions of risk

Liability of operators of nuclear power plants is limited and, as insurers of last resort, governments are naturally interested in risk assessments of nuclear safety. Risk assessment provides useful insights into insurability and the costs of a nuclear power accident. In the literature, limited liability as an implicit

[6] The reactor will provide about 12 TWh of electricity. The two companies, TVO and Areva, are in disagreement about the delays and have sued each other for claims of compensation of about 2.5 billion Euros each.

subsidy has been studied by Heyes and Heyes (2000) and, more generally, energy accidents and costs have been discussed by Sovacool (2008) and Felder (2009), among others. Estimates of probabilities of nuclear accidents have typically been calculated based on probabilistic risk assessments (PRA) or statistical analyses of historical data. Hofert and Wüthrich (2011) cite assessments reporting annual probabilities of $1 \cdot 10^{-6}$ with long-term health damage and annual probabilities of $1 \cdot 10^{-8}$ with high financial losses (exceeding 8 billion USD). Escobar Rangel and Leveque (2013) point out the discrepancy between PRA estimates of the industry and what has been observed in the history of nuclear power. Properly assessing the probability of a nuclear accident even using statistical methods is challenging, however, because of the scarcity of data on very rare events. Yet, historical frequencies of nuclear accidents can be observed, and Cochran (2011) provides a list of nuclear power reactors that have experienced fuel-damage or partial core-melt accidents, on which basis the estimated frequency of core-melt accidents is about one in 1,400 reactor-years.

Riddel (2011) has pointed out that the public has a difficult time quantifying risks from sources such as global warming or the generation, storage and transport of nuclear power, in part because there is no general consensus within the scientific community. In general, the communication of risk information is a sensitive policy process; previous research has found that people update their risk beliefs when new information becomes available to them (Viscusi et al 1991). How the information on scientific estimates on probabilities is perceived is reflected in concerns of the general public about nuclear accidents and their probability. When voters care about risks, policy-makers normally care about the concerns of their constituents. Sjöberg et al (2004) recognize that parliamentarians in Sweden and Norway now devote about three times as much attention to risk issues as they did in the first half of the 1960s.

In democratic societies, the importance of perceptions of risk in decision-making is recognized, but the challenge is how to measure them. Economists have long been resistant to data collected in surveys where self-reported expectations are elicited. This attitude was well captured thirty years ago by the renowned scholars in psychology, Slovic, Fischhoff and Lichtenstein, who have studied risk perceptions extensively: "One alternative is not to listen to the public at all. … or to study public opinions, but without asking people directly to express their views. Some economists, for example, argue that people's verbal expressions are poor indicators of their true preferences; one should always observe some actual behavior. Although appealing in principle, this position runs into difficulty because of the large number of untested assumptions needed to infer preferences from behavior." (Slovic et al 1982) Currently, economists increasingly utilize data on beliefs for estimation of preferences (see, e.g., Manski 2004, Dohmen et al 2011, Allcott 2013). Support for the use of self-reported risk attitudes elicited by surveys has recently been found by Lönnqvist et al (2014). When comparing a questionnaire measure with an incentivized lottery-choice task (Holt and Layry 2002), they found that the questionnaire measure was more stable and correlated with a personality measure and actual risk-taking behavior.

Here, we investigate risk perceptions as the source of social costs of nuclear power capitalized in voting behavior. We use data collected in a survey in which respondents were asked directly about their perceptions of various risks. The questions were framed in the political context of the Finnish parliamentary vote on licenses for new nuclear reactors. Before the empirical analysis we present the analytical framework on which the welfare estimates on social costs are based.

3. Simple model for estimation of perceived risk as shadow cost

Public policy is affected by public attitudes towards risks, which in turn have an influence on the social costs of alternative energy production technologies. We study how risk perceptions of nuclear energy production are related to decisions on licenses for new reactors.

Assume that there is a vote on new nuclear reactor capacity, R, when existing production capacity is K_0. Probability to vote for accepting license for nuclear reactor, p_f, depends on risk perceptions of accident at a nuclear power plant, r, such that the decision of an individual regarding whether he or she will vote in support of or against nuclear power reactor licenses can be given a utility-theoretic interpretation.

Social planner

The social planner maximizes the welfare of individuals and takes the utility and risk preferences reflected in the probability of voting for nuclear power, $p_f(r)$, as given. Hence, the probability can be considered as a utility weight in the social planner's welfare function. We hypothesize that increased risk perception decreases the probability of voting in favor of nuclear power, or ${p'}_f(r) < 0$. Risk perceptions, r, may differ from scientifically estimated, "objective" probabilities, $\bar{r}$. The social planner is concerned about *excessive* perceived risk ($r > \bar{r}$), which causes disutility, $D(r - \bar{r})$, $D'(r) > 0$.

The net benefits of energy production are $\pi_f(K_0 + R)$ for old capacity, K_0, and a new reactor, R, and $\pi(K_0)$ for capacity without an additional nuclear reactor. Hence, the objective function of the social planner reflects the utility weights of citizens and disutility of risk perceptions:

$$W = p_f(r)\pi_f(K_0 + R) + (1 - p_f(r))\pi(K_0) - D(r - \bar{r}). \quad (1)$$

If perceptions of risk of a nuclear accident are larger than objective probabilities, that is, $r > \bar{r}$, the social planner may consider reducing exaggerated risk perceptions to improve welfare. The impact of risk perceptions on social welfare can be estimated by totally differentiating W in equation (1) with respect to r such that[7]

$$\frac{\partial W}{\partial r} = p_f'[\pi_f(K_0 + R) - \pi(K_0)] - D'. \quad (2)$$

Equation (2) indicates that the marginal impact of higher risk perception equals the decreased probability of voting for nuclear power, p_f' (<0), times loss in expected electricity production ($\pi_f - \pi$) and increased disutility of excessive perceived risk, D'. This last term on the right hand side (RHS) can be estimated, for example, by hedonic pricing, in which risk perceptions are capitalized in the housing prices close to nuclear reactors after an accident (see, e.g., Bauer et al. 2013 for a most recent study). The purpose of this paper is to estimate the first term on the RHS, in which risk perceptions are capitalized in voting behavior. The marginal impact of risk perception on the choice of citizens to favor or oppose new licenses for nuclear power is the parameter to be estimated from the citizens' preferences.

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[7] Alternatively, this may be viewed as the social planner considering how much costly effort, a, to put on reducing exaggerated risk perceptions to improve welfare. Hence, the social planner maximizes welfare

$W = p_f(r - a)\pi_f(K_0 + R) + \left(1 - p_f(r - a)\right)\pi(K_0) - D(r - \bar{r} - a) - c(a)$ with respect to efforts such that $\frac{\partial W}{\partial a} = -p'_f\pi_f + p'_f\pi + D' - c' = 0$ or $c' = -p_f'(\pi_f - \pi) + D'$.

Citizens' preferences

Indirect utility associated with preferences for nuclear energy production is a function of deterministic variables – socioeconomic characteristics, s, and risk perceptions, r, - plus an additive error term, ε, which is unknown to the researcher:

$$U_{iR} = \propto_R + s'_i\beta_R + r'_i\rho_R + \varepsilon_R$$
$$U_{i0} = \propto_0 + s'_i\beta_0 + r'_i\rho_0 + \varepsilon_0 \qquad (3)$$

where U_{iR} and U_{i0} represent the *i*th individual's indirect utility associated with the choice whether to vote in favor of additional reactor capacity, indicated by sub-index R, or against, 0. Rational behavior implies that voting in favor of a nuclear reactor is preferred if $U_{iR} > U_{i0}$, and against if $U_{iR} < U_{i0}$.

Accordingly, the probability p_f that the *i*th individual votes in favor of reactor capacity can be written as follows:

$$p_f = p(U_{iR} > U_{i0}) = p[\varepsilon_{i0} - \varepsilon_{iR} < \propto_R - \propto_0 + s'_i(\beta_R - \beta_0) + r'_i(\rho_R - \rho_0)]$$
$$= F[(\propto_R - \propto_0) + s'_i(\beta_R - \beta_0) + r'_i(\rho_R - \rho_0)] \qquad (4)$$

where *F* is the distribution function of $\varepsilon_{i0} - \varepsilon_{iR}$. Assuming that the errors follow a logistic distribution and denoting $\alpha = \propto_R - \propto_0$, $\beta = \beta_R - \beta_0$, $\rho = \rho_R - \rho_0$, we have a standard logit model $p_f = p(U_{iR} > U_{i0}) = 1/[1 + e^{\propto + s_i'\beta + r_i'\rho}]$. The logarithm of odds ratios for favoring nuclear power can be expressed as a linear function of the explanatory variables chosen, or

$$ln\left(\frac{p_f}{1-p_f}\right) = \alpha + s_i'\beta + r_i'\rho. \qquad (5)$$

Hence, the probability of an individual voting for nuclear power is a function $p_f(r;s)$, and the vectors of the coefficients to be estimated are ρ for risk perceptions, *r*, and β for socioeconomic variables, *s*. For purposes of our analysis, the most important explanatory variable is the perceived risk of a nuclear power plant accident. In the following estimations, we first apply a linear probability model for the voting decision, and then contrast it with Logit modelling. Several approaches are adopted for robustness checks.

4. Data

This section provides background on the citizen mail survey. It describes the survey implementation, outlines the questions asked on voting and risk perceptions and presents descriptive statistics.

4.1 Survey implementation and measurement of risk perceptions

The data were collected using a mail survey focused on Finnish energy policy with a special emphasis on nuclear power. The implementation of the survey followed the tailored design method of Dillman et al. (2009). Pre-testing included expert reviews, as well as a mail survey to the members of the Finnish Parliament in spring 2011[8]. A survey proper with a random sample of 1000 citizens was conducted in October - December 2012. The respondents were contacted three times after the first delivery of the survey questionnaire using mail reminders (first a reminder card and then two follow-up letters with re-mailed questionnaires after three and five weeks from the first mailing). The survey achieved a response rate of 52 %.[9]

The questionnaire consisted of thematically grouped questions presented in a logical order starting with the issues most familiar to the respondents regarding energy consumption, for example, and ending with questions on the respondents' socio-economic background. The most important parts of the survey for our analysis were those that included an item regarding a putative vote on nuclear power and a set of questions on risk perceptions. The vote was formulated as a referendum-type question. The question was framed in a manner similar to that used for the actual voting decision by the Finnish members of Parliament in July 2010. The question read: "Had there been a referendum on nuclear power plant licenses, how would you have voted?" The answer choices were "a license for one reactor", "licenses for two reactors", "no license" or "don't know".

The question on voting was followed up by a survey item eliciting the respondents' perceptions with a battery of questions on risks related to energy supply in the economy. The risks to be assessed were unemployment, energy self-sufficiency, the competitiveness of the Finnish economy, an increase in greenhouse gases, nuclear waste, an accident at a nuclear power plant, health impacts of small particles generated in energy production, the increased land area required for production of bioenergy and

[8] See Aatola and Huhtala (2014)

[9] To check the robustness of the results to nonresponse, a telephone follow-up survey was conducted for a sample of 100 non-respondents; the response rate was 50%.

failures in saving energy. The respondents were asked to evaluate the risks on a five-point Likert scale (1='low risk', 2='fairly low risk', 3='cannot say', 4='fairly high risk', 5='high risk'). The exact wording of the question on risk perceptions is given in Appendix A.

4.2 Descriptive statistics

Table 1 shows the summary statistics of the data. Our sample comprises some 500 observations (indicated in column 'N'). For comparison, Table 1 presents demographic information on the Finnish population at large as well as on the members of Parliament (MPs) who participated in the actual parliamentary vote on licenses for nuclear reactors in 2010 (column MP2010). There are 200 members in the Finnish Parliament, of whom 190 voted on the licenses; 10 were absent or did not cast a vote.

Voting in favor of one or two license applications is coded as a "yes" for additional nuclear power in our data set. Licenses for nuclear power were supported by 49 percent of the citizen respondents (row indicating 'Voting' in Table 1). This is less than the proportion of MPs supporting nuclear power in the actual vote, which was 66 percent. However, opinion polls carried out and published prior to the vote suggested that there might have been a much closer vote in Parliament, as about 50 percent of the general public supported nuclear power in the polls (Energiateollisuus 2010).

Age is the only continuous explanatory variable; all other variables are binary dummy variables or are based on interval data. The average age of the citizen respondents, 51 years, is higher than the average of the Finnish population (42 years), but very close to the average age of the MPs who actually participated in the vote (52 years). In the sample of citizen respondents, the distribution of gender was even, that is, 50 percent women and 50 percent men, which equals the proportion of males among the Finnish population, 49%. Among the MPs at the time of the vote, the proportion of men was 60%.

In Table 1, a dummy variable for high level of education indicates an academic degree (0,1), a qualification held by roughly 20 % of the citizen respondents. A dummy variable for high income indicates whether the respondent has a household gross income of 5200 euros or higher per month. The proportion of respondents by constituency follows the distribution of MPs in Parliament; the constituency dummies are indexed geographically from south (I) to north (XII).

The lowermost part of Table 1 shows means of responses for each risk perception queried. The risk of nuclear waste has the greatest mean, followed by risk of accident, whereas the risk of increased unemployment yields the lowest mean. Failure in energy saving has the third largest mean and the smallest standard deviation. Standard deviation is greatest for risk of accident.

In Figure 1a, the summary variable “average risk perception” illustrates the overall distribution of risk perceptions in the sample. The histogram “average risk perception” indicates a mean of responses to all questions on perceptions of risk, that is, the nine risks presented for assessment. The distribution of average risk perception by gender (Figure 1b) reveals different patterns for men and women, with men being more likely to indicate lower risk perceptions than women. This pattern is in line with previous findings on the differences in general risk attitudes by gender (e.g., Croson and Gneezy 2009). In particular, women typically report higher perceptions of the probability of negative consequences than men (Weber et al. 2002, Harris et al 2006).

5. Results

5.1 Determinants of risk perceptions

Ultimately, we are interested in assessing the impact of a perceived risk of an accident at a nuclear power plant on the public opinion on new nuclear power reactor licenses. For this purpose, it is important to gain insight into the determinants of the stated risk perceptions, or subjective risks. We begin by regressing the respondents’ answers to the question on the perceived risk of an accident on socioeconomic characteristics such as gender, age, education and income. As explanatory variables we also include dummy variables for the status of being unemployed or an entrepreneur. Moreover, by including the constituencies as dummies we can control for regional fixed effects.[10]

Table 2 reports the results for linear regressions on the determinants of risk perceptions. We are especially interested in the risk perceptions regarding a nuclear power plant accident reported in column (1). Male gender, high education and high income have a statistically significant impact on

[10] Finland is divided into 13 constituencies. In our estimations, the constituency of Helsinki is used as a baseline category, and the constituency dummies (in roman numbers) are running from south (I) to north (XI). We have excluded from our survey one constituency, the Aland Islands which has an autonomous status in the Finnish constitution; hence, the actual number of constituency dummies is eleven.

perception of the risk of an accident: High education and male gender decrease the risk, whereas high income tends to increase it.

Gender has the strongest impact on the perceived risk of a nuclear power plant accident. On average, men consider the risk to be lower by 0.7 points, measured on a five-point scale, when compared to women. The relatively large difference by gender can be seen in Figure 2, where the histograms for perceived accident risk are depicted separately for men and women. About 27 percent of men consider the risk of an accident 'high' or 'fairly high', whereas the corresponding rate among women is twice as high, or 53 percent.

To compare the perceived accident risk with other stated risk perceptions elicited in the survey, we present regressions for two summary indicators on risk perceptions as dependent variables. "Average risk perception" is calculated as an average of the responses to the entire battery of risk questions regarding energy policy. The other summary indicator includes the average of all risk responses with the exception of those for risk of accident. For the average risk perception, we detect a similar tendency among men and highly educated persons to express lower risk perceptions, but the marginal impacts are more modest than in the case of accident risk. In addition, the coefficient for the indicator variable entrepreneur is negative and statistically significant. The rightmost column (3) shows the results where the risk of accident is excluded from the average risk indicator; the coefficients that are statistically significant in this instance are age and male gender, with decreasing impacts on perception of risk.

We carried out separate linear regressions for risk perception responses to all risk elicitation questions in Appendix A; the results are reported in Table B1 in Appendix B. The regressions suggest that age and male gender have a statistically significant and negative impact concerning the risk perceptions of greenhouse gases, small particles, and energy saving. An interesting detail which increases the credibility of the context-specific and self-reported risk perceptions is that an increase in unemployment is perceived as more risky by those who indicated that they were unemployed at the time of the survey (second column in Table B1); the impact is statistically significant.

Finally, Table 3 shows the correlations between the stated risk perceptions regarding different contexts and consequences of energy policy. The economic risks – increased unemployment, decreased self-sufficiency and decreased competitiveness - have relatively high cross-correlations. Correlations are high also between environmental issues related to increases in greenhouse gases and small particles from burning fossil fuels. For our analysis, the most important correlations are those relating to the perception of the risk of a nuclear power plant accident. Obviously, the correlation between a perceived risk of accident and nuclear waste is the largest, followed by that between the risk of accident and health-impairing small particles. We will utilize this finding when we study the robustness of our results on the self-reported accident risk assessment.

5.2 Risk perceptions and voting on licenses for nuclear power reactors

We estimate the voting probabilities that capture the respondents' preferences regarding nuclear power. An individual votes either in support of or against licenses for nuclear reactors, and this decision is explained by a set of explanatory variables, individual characteristics and risk perceptions. As the perception of risk is measured as interval data, the marginal impact of risk perception measures a change from one risk category to the next on the five-point scale. We will investigate the impact on the results of the interval scale used in the risk assessment in section 5.3.

We are interested especially in the impact of the perceived risk of accident on voting. To gain insight into the relative impact of accident risk compared to perceptions of other risks, we also report two alternative models, in which the voting decision is regressed on two summary indicators of risk perceptions (the same indicators for which the determinants were reported in Table 2). In addition, we rescale perception of accident risk by subtracting average risk perception, excluding accident risk from it. Table 4 shows results for three models estimated using a linear probability model in which the dependent variable is a binary variable indicating voting behavior (1='in favor', 0='against').

All risk perception measures are significant explanatory variables, providing confirmation of their validity regarding the focal behavior. The marginal impacts of all risk measures are negative but, not surprisingly, the context-specific risk, perceived accident risk, has the largest impact on voting on nuclear reactor licenses. Even when the respondent's use of the risk scale is taken into account in the measure of perceived risk accident in the regression reported in column (3), accident risk figures substantially, and remains a statistically significant determinant.

In Table 4, we report coefficient estimates for the control variables as well. Age and gender are both positive and statistically significant in all models and their impact is of relatively similar magnitude across the models. The coefficient for male is largest in the model controlling for the average risk excluding accident risk. Neither high education nor high income is statistically significant in any of the models.

5.3 Robustness and alternative modeling approaches

Risk perceptions in general – and perception of accident risk in particular, which we are interested in here – seem to have an impact on citizens' views on granting licenses for new nuclear power reactors. To investigate further the robustness of the regression results in Table 4, we carried out estimations using several alternative model specifications. For comparison, Table 5 shows the results for OLS and Logit models where demographics (age, gender, education and income) and dummies for constituency are included as explanatory variables. The results of the Logit models are reported for the marginal effects of coefficients at means to make them comparable with the OLS coefficients. Both modelling approaches yield rather similar coefficients.

In the first two columns, the results are reported for specifications with an alternative indicator variable that scales the perception of accident risk ('accident risk scaled'). Scaling of the accident risk is carried out by calculating the average of responses to all items eliciting risk perceptions with the exception of accident risk and then subtracting the average from the perception of accident risk. The purpose is to standardize the respondent's use of the Likert scale across the items eliciting different risk perceptions. Hence, the coefficient captures the impact of the extent to which the respondent's perception of accident risk deviates of his or her assessed and perceived risks in items other than an accident. As can be seen in columns (1) and (2), the marginal impacts for the scaled variable are slightly smaller than for the measure of accident risk without scaling in columns (5) and (6).

In columns (3) and (4), accident risk is measured with two dummy variables. The first one receives a value of one if the respondent has chosen the 'cannot say' option (Accident risk=3 on the Likert scale). The second yields a value of one if accident risk is regarded as 'fairly high' or 'high' and zero otherwise (Accident risk=4 or 5 on the Likert scale). Hence, the baseline consists of responses of 'low' or 'fairly low' perceived risk. These dummy variables allow us to control for the respondent's use of the Likert scale. We contrast low perceived risk with ambiguity (cannot say), on the one hand, and, on the other, with relatively high stated perceived risk. The results show that regarding the risk of accident as fairly high or high (value 4 or 5) lowers the probability of voting in favor of nuclear power reactors considerably, or over 40 percent. The probability decreases also when the respondent has indicated ambiguity regarding the risk of accident by choosing 'cannot say' (middle point, or value of 3, on the Likert scale). The coefficients for the two risk dummies are statistically significant.

The results show that the impact of the risk of accident is robust; the marginal impact is always negative and statistically significant, and remains rather stable. The non-linear Logit model produces consistently slightly larger marginal impacts than OLS. In general, the results show that the higher the respondent regards the risk of accident, the lower the probability of his or her voting in favor of nuclear power.

5.4 Measurement of perceived risk and reverse causality

Our findings suggest that perceived risks of accident indeed matter for citizens when considering nuclear power as an energy source. The results do not seem to be sensitive to the modeling approach chosen. However, one concern may be how to interpret the self-reported perceptions of the risk of an accident. Obviously, when the respondents state that the risk is 'fairly high' or 'high', they are not considering objective probabilities, which in absolute terms are very small (as discussed in section 2.2), or orders of magnitude smaller than a 'high' perceived risk. Indeed, it is likely that the citizens are considering not only the probability of an accident but also its potential detrimental consequences. Hence, we should treat the perceptions as indicators that are compromised by measurement errors. The second concern is related to the issue of reverse causality. This problem arises in our welfare analysis as estimates are based on stated perceived risks and intended behavior regarding the voting decision. To tackle these problems we pursue an instrumental variable approach in this section.

Previous research suggests that objective probabilities are good candidates as instruments for subjective, or perceived, risks. However, for obvious reasons, an estimated objective risk of a future nuclear-power-plant accident is difficult to operationalize at the respondent level in our data set. Therefore, we resort to past experiences of the most severe nuclear power plant accidents in the world, or Chernobyl in 1986 and Fukushima in 2011. The occurrences of these two accidents (classified in the highest severity category on a 7-point scale) are exogenous to the respondents, and we exploit this fact in creating instruments. The literature suggests that world-views and attitudes are influenced by drastic events in young adulthood in particular. Hence, we form two dummies for those who were young adults at the time of the two accidents. The upper limits for the age groups within a range of five years are identified by the age by which about 90 percent of the cohort has moved out of their childhood home and no longer lives with their parents. In 2011, this age was 26 years, whereas in 1986 it was 30 years, reflecting the fact that young adults leave their childhood home earlier and earlier. Hence, we have two dummies, one for those who were between 22 and 26 years old at the time of Fukushima and the other for those who were between 26 and 30 years old at the time of Chernobyl.

Our second, alternative instrument is based on responses to a survey item eliciting the perceived health risk caused by small particles in energy production. This risk factor is clearly correlated with the risk of accident and other environmental risks (Table 3). Yet, at the same time, very few of the respondents claimed directly that it was an important factor in the voting decision. When asked about the importance of this factor when voting on nuclear power, only 1.5 percent of the respondents indicated that small particles were important. Therefore, we hypothesize that the variable captures general environmental attitudes of the respondents, attitudes that prevail when they consider all of the other risks.

Table 6 shows the results of a second stage of 2SLS. In the first two columns of Panel A, the perception of accident risk is instrumented by two age-group dummies and, in the next two columns, by the perceived health risk of small particles. In columns (2) and (4) fixed effects for constitutions are controlled for in the regressions as well, and the results are not sensitive to whether they are included or not. Accident risk remains statistically significant in all model variants. When the perceived risk of small particles is used as the instrument, the coefficient for accident risk almost doubles. The F-test statistic is also particularly high for this instrument. The results strengthen our confidence in the perceived risk of accident as a strong determinant of the voting decision of the respondents.

Furthermore, as there is a persistent difference between genders regarding nuclear power in that men show a larger likelihood to support new nuclear reactor licenses than do women, we investigated the working of instruments in two subsamples, split by gender. In Panel B of Table 6 we see that here, too, the perceived risk of accident is negative and statistically significant and larger than in the corresponding OLS model in column (6) of Table 5. The coefficient is even larger for men than for women.

6. Policy implications

It seems evident that the marginal impact of perceiving the risk of accident as being high is large, and considerably reduces the willingness to support licenses for new nuclear reactors. Using the estimated marginal impacts of the accident risk on predicted voting behavior, we can roughly approximate the magnitude of the impact of increased risk perceptions on the value of the electricity production lost due to opposition to new nuclear reactors. In Section 3, the avoided loss of expected electricity production was derived to be $-p'_f(\pi_f - \pi)$ in equation (5), where $(\pi_f - \pi)$ is the net increase in the electricity production at stake in a vote on licenses. Here, we have estimated the marginal impact of increased perceived risk on voting probability, p'_f, or the coefficient for the perceived risk of an accident.

We estimate the annual production of a new nuclear power plant to be about 12 TWh, which is the capacity of the reactor currently under construction in Finland, the license for which was first denied but, after ten years, accepted. Using the marginal impact of perceptions of accident risks from the previous models (Tables 4, 5 and 6) and assuming the price of electricity to be 60€/MWh, our back-of-the-envelope calculation estimates the delay or loss of production as ranging from 70 to 380 million euros per annum. This is a considerable sum of money. If the perceptions 'fairly high' or 'high' risk of nuclear accident expressed in the survey are considered exaggerated compared to the objective risks, decision-makers may become interested in investing in measures to reduce anxiety regarding the risks and thereby increase welfare. In any case, this is the social cost of risk perceptions capitalized in voting behavior.

7. Conclusions

Drawing on Finnish survey data on the risk perceptions of the general public in a context of a referendum-type vote on permits for nuclear power, we show that risk perceptions do affect voting behavior. Various model specifications show that the estimated perceived high risk of nuclear accident decreases considerably the probability of voting in support of licenses for new nuclear reactors. The majority of those who are against nuclear power perceive the risk of accident as 'high' or 'fairly high'.

These perceived risks are extremely high compared to the scientifically estimated probabilities of accidents.

Previous studies have shown that people have difficulties in quantifying risks from complex issues such as global warming and nuclear power. Thus their concern associated with these issues is more likely to be based on perceptions of risk than on scientific estimates of probabilities. In future research, risk perceptions of the citizens and the members of Parliament regarding nuclear power could be investigated in more detail, as the latter group should be better informed about the risks. As biased risk perceptions may pose costs to the society, ascertaining and understanding people's risk perceptions can help to reduce expenditures and disutility from uncertainty and to improve risk management and social welfare.

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Table 1. Descriptive statistics

Variable	Citizen Survey 2012 Mean	SD	Min	Max	N	Population 2010 Mean	Members of Parliament 2010 Mean	SD	Min	Max	N
Voting	0.49	0.50	0	1	516	N.A.	0.66	0.47	0	1	190
Demographics											
Age	50.98	15.17	18	76	509	42	51.54	10.26	28	72	199
Male	0.50	0.50	0	1	510	0.49	0.6	0.49	0	1	199
High education	0.23	0.42	0	1	508	0.25	0.63	0.48	0	1	199
High income	0.22	0.42	0	1	496		1	0	1	1	199
Entrepreneur	0.06	0.24	0	1	507		0.15		0	1	199
Unemployed	0.06	0.23	0	1	507						
Constituencies											
I	0.08	0.28	0	1	517		0.12	0.32	0	1	198
II	0.16	0.37	0	1	517		0.16	0.37	0	1	198
III	0.07	0.26	0	1	517		0.08	0.27	0	1	198
IV	0.05	0.23	0	1	517		0.05	0.21	0	1	198
V	0.08	0.27	0	1	517		0.07	0.26	0	1	198
VI	0.09	0.29	0	1	517		0.09	0.29	0	1	198
VII	0.09	0.28	0	1	517		0.09	0.29	0	1	198
VIII	0.08	0.27	0	1	517		0.08	0.27	0	1	198
IX	0.08	0.27	0	1	517		0.09	0.28	0	1	198
X	0.06	0.23	0	1	517		0.05	0.22	0	1	198
XI	0.10	0.30	0	1	517		0.09	0.28	0	1	198
XII	0.06	0.23	0	1	517		0.04	0.19	0	1	198
Risk perceptions[1)]											
Accident	2.90	1.44	1	5	505						
Self-sufficiency	2.68	1.15	1	5	497						
Unemployment	2.53	1.17	1	5	505						
Greenhouse gases	2.70	1.23	1	5	498						
Nuclear waste	3.54	1.36	1	5	509						
Competitiveness	2.76	1.11	1	5	498						
Small particles	2.79	1.23	1	5	504						
Land from food to bioenergy	2.55	1.16	1	5	501						
Failure in energy saving	2.84	1.05	1	5	504						
Average risk perception	2.82	0.70	1	5	512						

1) For the exact wordings used for elicitation of risk perceptions, see Appendix A.

Table 2. Primary determinants for perceived accident risk and for alternative summary indicators for risk perceptions

Variable	Accident risk perception[1)] [1]	Average risk perception [2]	Average risk perception excluding accident risk [3]
Age	0.007 (0.004)	-0.002 (0.002)	-0.005** (0.002)
Male	-0.743*** (0.132)	-0.295*** (0.066)	-0.252*** (0.067)
High education	-0.435*** (0.163)	-0.150* (0.081)	-0.079 (0.082)
High income	0.256* (0.154)	-0.011 (0.077)	-0.047 (0.078)
Entrepreneur	-0.147 (0.274)	-0.234* (0.137)	-0.200 (0.137)
Unemployed	0.194 (0.293)	-0.011 (0.142)	-0.046 (0.147)
Constituencies	yes	yes	yes
Constant	2.918*** (0.338)	3.153*** (0.169)	3.170*** (0.170)
N	468	474	440

1) Measured on Likert scale 1-5

Table 3. Correlations between risk attitudes

	Nuclear accident	Self-sufficiency	Unemployment	Greenhouse gases	Nuclear Waste	Competitiveness	Small particles	Need for biomass area	Energy saving	Average risk perception
Nuclear accident	1.000									
Self-sufficiency	0.039	1.000								
Unemployment	-0.011	0.442	1.000							
Greenhouse gases	0.196	0.425	0.293	1.000						
Nuclear Waste	0.676	-0.030	0.008	0.187	1.000					
Competitiveness	-0.039	0.561	0.482	0.333	-0.070	1.000				
Small particles	0.348	0.317	0.245	0.570	0.361	0.308	1.000			
Need for biomass area	-0.064	0.234	0.102	0.135	-0.076	0.186	0.185	1.000		
Energy saving	0.214	0.260	0.199	0.281	0.217	0.256	0.365	0.230	1.000	
Average risk perception	0.517	0.616	0.525	0.674	0.496	0.563	0.737	0.358	0.576	1.000

Table 4. Risk perceptions and voting on nuclear power

Dependent variable:	Voting on nuclear power (1=in favor, 0=against)		
	(1)	(2)	(3)
Age	0.003**	0.002	0.004***
	(0.001)	(0.002)	(0.001)
Male	0.225***	0.302***	0.272***
	(0.041)	(0.045)	(0.043)
High education	0.027	0.083	0.052
	(0.050)	(0.055)	(0.053)
High income	-0.014	-0.070	-0.034
	(0.047)	(0.052)	(0.050)
Accident risk (1–5)	-0.146***		
	(0.014)		
Average risk excluding accident risk (1-5) [1)]		-0.116***	
		(0.033)	
Accident risk scaled[2)] (-3.5 – 3.4)			-0.120***
			(0.016)
Constant	0.647***	0.581***	0.188**
	(0.088)	(0.135)	(0.083)
Number of observations	471	444	442
Adjusted R2	0.27	0.13	0.21

1) Average of items eliciting risk perceptions, except accident risk (for these 8 items eliciting risk perceptions, see Appendix A)
2) Average risk, excluding accident risk (i.e. average of responses to all items eliciting risk perceptions, with the exception of accident risk) is subtracted from accident risk

Table 5. Logit (marginal impacts) and OLS estimations: sensitivity of the impact of perceived nuclear power plant accident risk on voting

Variable	Logit (1)	OLS (2)	Logit (3)	OLS (4)	Logit (5)	OLS (6)
Age	0.005*** (0.002)	0.004*** (0.001)	0.005*** (0.002)	0.003** (0.001)	0.005*** (0.002)	0.003** (0.001)
Male	0.307*** (0.052)	0.261*** (0.045)	0.277*** (0.054)	0.211*** 0.042)	0.277*** (0.053)	0.216*** (0.042)
High education	0.095 (0.071)	0.072 (0.054)	0.091 (0.072)	0.059 (0.050)	0.070 (0.072)	0.050 (0.051)
High income	-0.027 (0.067)	-0.019 (0.051)	-0.026 (0.068)	-0.013 (0.047)	-0.009 (0.068)	-0.002 (0.048)
Accident risk scaled (-3.5-3.4)[1)]	-0.154*** (0.023)	-0.121*** (0.016)				
Accident risk=3			-0.359*** (0.062)	-0.341*** (0.072)		
Accident risk=4 or 5			-0.506*** (0.046)	-0.448*** (0.043)		
Accident risk (1-5)					-0.188*** (0.022)	-0.145*** (0.015)
Constant		0.098 (0.111)		0.378*** (0.105)		0.580*** (0.112)
Constituencies (dummies I-XII)	yes	yes	yes	yes	yes	yes

1) Average risk excluding accident risk (i.e. average of responses to all items eliciting risk perceptions, with the exception of accident risk) is subtracted from accident risk

Table 6. Instrumental variable (IV) estimations: sensitivity of the impact of perceived nuclear power plant accident risk on voting

	A. IV Results for total sample [1)]			
Variable	(1)	(2)	(3)	(4)
Accident risk	-0.143* (0.076)	-0.145** (0.072)	-0.263*** (0.044)	-0.259*** (0.043)
Age	0.003** (0.001)	0.003** (0.001)	0.004*** (0.001)	0.004*** (0.001)
Male	0.227*** (0.070)	0.216*** (0.066)	0.137*** (0.053)	0.135*** (0.053)
High education	0.029 (0.060)	0.050 (0.060)	-0.024 (0.056)	-0.002 (0.056)
High income	-0.015 (0.051)	-0.002 (0.050)	0.016 (0.052)	0.025 (0.051)
Constant	0.637*** (0.238)	0.581*** (0.235)	0.990*** (0.153)	0.916*** (0.167)
Constituencies	no	yes	no	yes
N	471	470	467	466
F-test for instrument	8.51	9.32	64.54	64.50

	B. IV Results by sub-sample[2)]			
Subsample	female	male	female	male
Coefficient	-0.110	-0.177***	-0.228***	-0.285***
N	238	232	235	231
F test	2.47	8.43	37.55	25.04

1) Instruments used: in columns 1 and 2 dummies for accidents in young adulthood and in columns 3 and 4 risk of small particles and health impairment due to burning of fossil fuels
2) Dummies for constituencies included

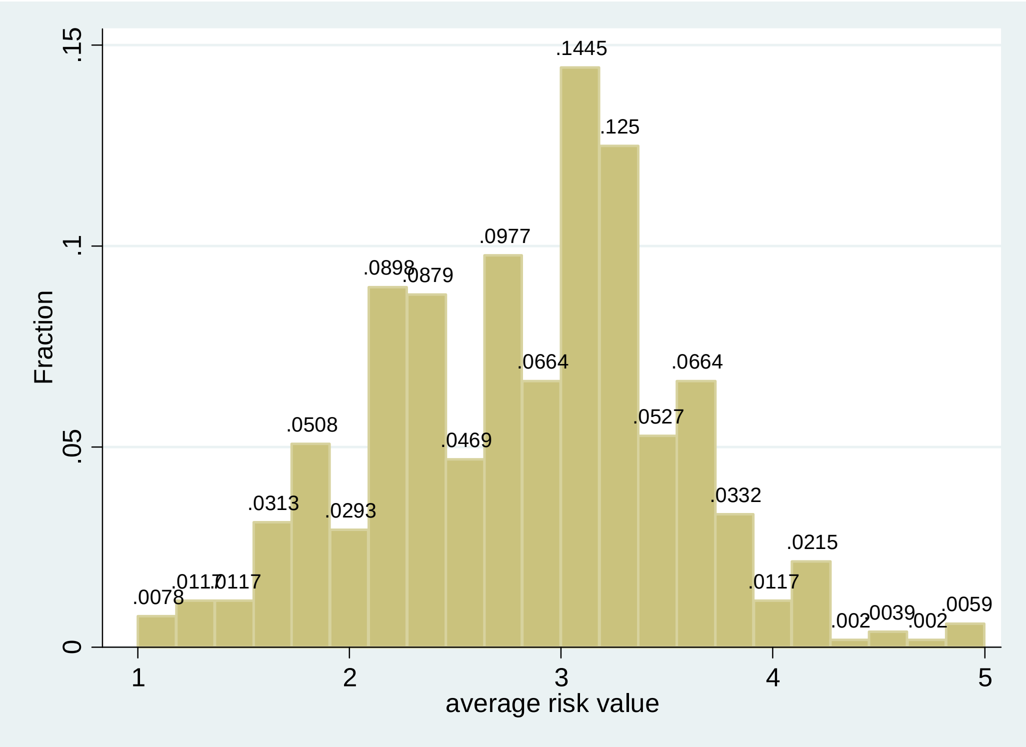

Figure 1 a. Histogram of elicited risk perceptions, average of nine risk evaluations (measured on a five-point scale 1= low risk; 5=high risk)

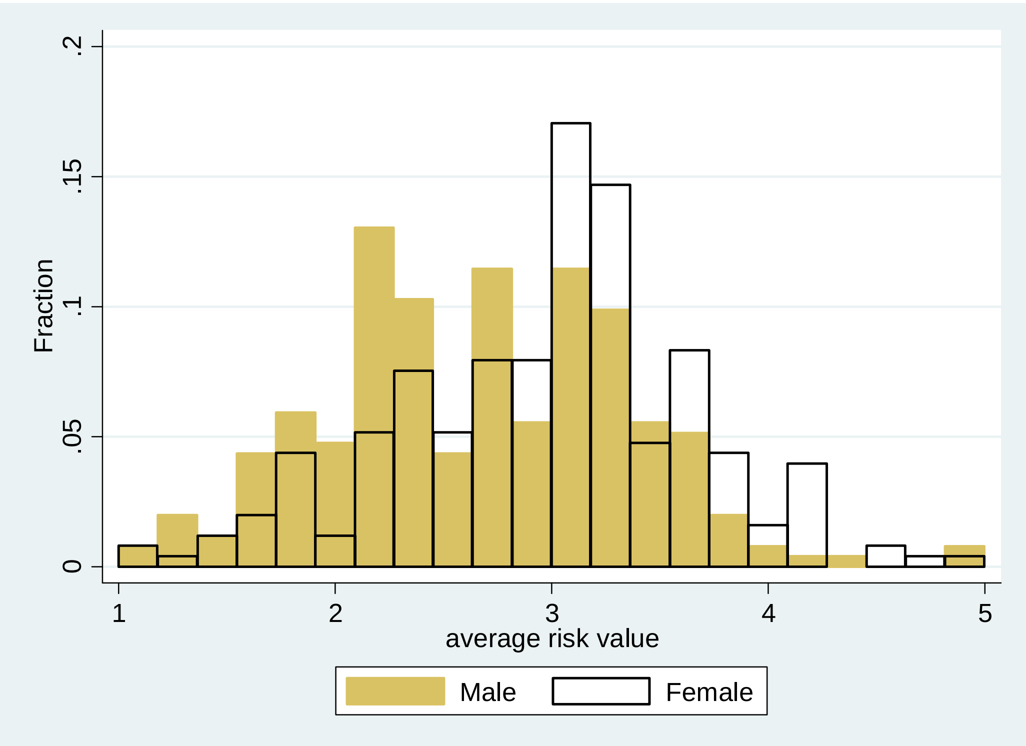

Figure 1 b. Histogram of elicited risk perceptions by gender, average of nine risk evaluations (measured on a five-point scale 1= low risk; 5=high risk)

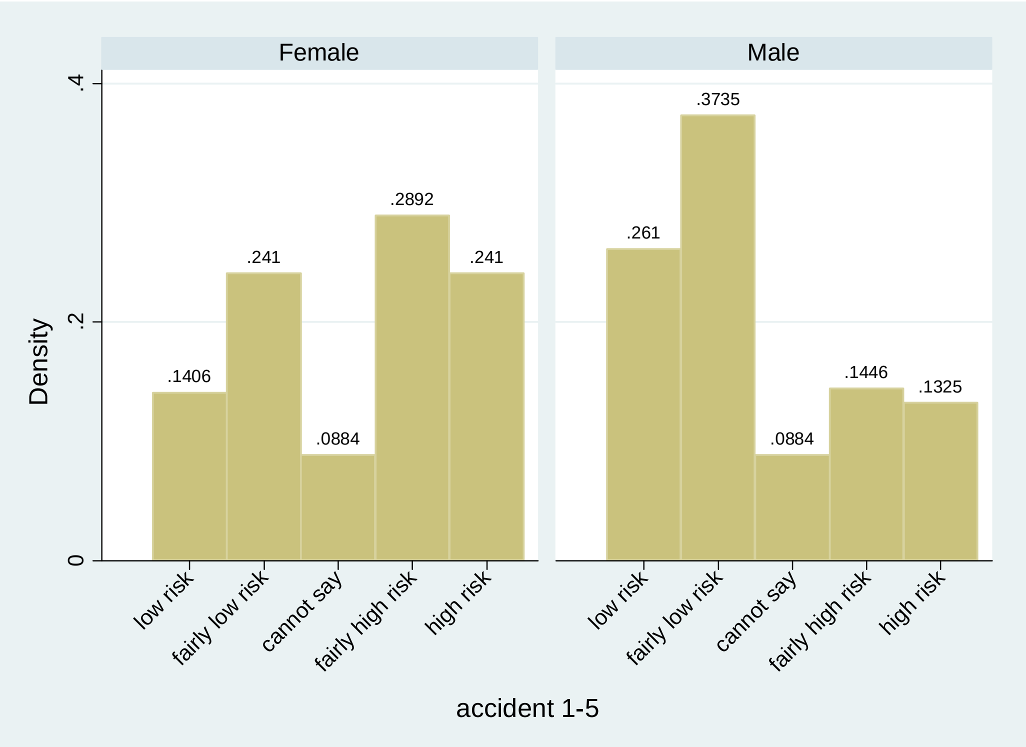

Figure 2. Histograms of responses to perceived risk of accident at nuclear power plant by gender.

Appendix A

Exact wording of the item eliciting risk perceptions:

"Consider your vote regarding additional nuclear reactor. How important are the following risks for Finland in your opinion?

- Increase in unemployment
- Decreasing energy self-sufficiency
- Increase in greenhouse gases
- Radioactive nuclear waste
- Weakening competitiveness of the economy
- Small particles in energy production impairing health
- Bioenergy production taking land from food production
- Accident at nuclear power plant
- Failure in energy-saving"

Appendix B

Table B1

Variable	Self Sufficiency	Unemployment	Greenhouse gases	Nuclear Waste	Competitiveness	Small Particles	Land for Bioenergy	Energy Saving
Age	-0.003 (0.004)	-0.007* (0.004)	-0.007* (0.004)	-0.002 (0.004)	0.000 (0.004)	-0.007* (0.004)	0.002 (0.004)	-0.007** (0.003)
Male	-0.063 (0.111)	0.088 (0.113)	-0.541*** (0.117)	-0.597*** (0.126)	0.013 (0.108)	-0.553*** (0.116)	0.013 (0.112)	-0.193* (0.102)
High Education	0.066 (0.136)	-0.145 (0.138)	-0.056 (0.144)	-0.463*** (0.155)	0.218* (0.132)	-0.189 (0.142)	-0.056 (0.138)	-0.116 (0.125)
High Income	0.060 (0.130)	-0.195 (0.131)	-0.077 (0.136)	0.021 (0.147)	-0.093 (0.126)	-0.095 (0.135)	-0.144 (0.131)	0.163 (0.118)
Entrepreneur	-0.345 (0.227)	-0.157 (0.233)	-0.394* (0.239)	-0.224 (0.261)	-0.105 (0.225)	-0.216 (0.239)	-0.288 (0.232)	-0.131 (0.210)
Unemployed	0.095 (0.235)	0.460* (0.241)	-0.296 (0.247)	-0.079 (0.274)	0.244 (0.229)	-0.095 (0.247)	-0.262 (0.244)	-0.224 (0.221)
Constituencies	yes	yes	yes	yes	yes	yes	yes	yes
Constant	2.978*** (0.283)	2.953*** (0.288)	3.224*** (0.298)	4.192*** (0.322)	2.496*** (0.276)	3.542*** (0.296)	2.449*** (0.288)	3.267*** (0.260)