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Anni Huhtala
Piia Remes

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Anni Huhtala, Research Director, VATT Institute for Economic Research

Piia Remes, Senior Researcher, VATT Institute for Economic Research

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VATT Institute for Economic Research
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Quantifying the social costs of nuclear energy: Perceived risk of accident at nuclear power plant

Anni Huhtala* and Piia Remes

VATT Institute for Economic Research

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Abstract

The preferences expressed in voting on nuclear reactor licenses and the risk perceptions of citizens provide insights into social costs of nuclear power and decision making in energy policy. We show analytically that these costs consist of disutility caused by unnecessary anxiety - due to misperceived risks relating to 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 utilizing alternative risk rating scales and framing in elicitation of risk perceptions associated with nuclear power across contexts. We 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. This result holds across a number of robustness checks including an instrumental variable estimation and a model validation by observed voting behavior of the members of Parliament. The public's risk perceptions translate into a significant social cost, and are likely to affect the revenues, costs and financing conditions in the nuclear power sector in the future.

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

JEL classification: C25, C26, C83, D62, Q48, Q58

*+358-295 519 414, anni.huhtala@vatt.fi, http://www.vatt.fi/en/anni-huhtala

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1. Introduction

Nuclear power is a contentious subject in energy policy. It supplies base-load energy with low operational costs and does so without CO_2 emissions, a feature that appeals to the international community in tackling climate change. However, 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. Safety risks have typically been considered the most challenging external costs of nuclear power (e.g., Kessides 2010). 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.

In this paper, we study the costs to society of the risks of nuclear power plant accidents. These costs are considerably harder to quantify than the costs of storage of spent fuel (Davis 2012). How should such external costs be assessed? Two salient elements must be considered in doing so. The first is the objective probability of accidents at nuclear power plants. These probabilities are small, but the consequences of a large-scale catastrophe are potentially vast and long-lasting. Interestingly in this regard, private insurance companies will not provide full-coverage insurance against accidents. This policy can be attributed to a choice made in the beginning of nuclear programs worldwide to implement a rule strictly limiting civil liability in order to allow the growth of the nuclear industry (Faure and Fiore, 2009). In the case of an extreme emergency, clean-up and compensation to victims for damage and injury are ultimately the responsibility of government.[1]

The second element is the impact on welfare of the perceived risks of a nuclear power plant accident. This is the focus of our paper. As the probability of a large-scale accident is very small, but the resulting damage may be enormous, the likelihood of an accident and the scope of the ensuing damage may become confounded in people's minds and result in exaggerated perceptions of risk.[2] It is thus

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

[2] "Risk perception is the *subjective assessment of the probability of a specified type of accident* happening and how concerned we are with the consequences. To perceive risk includes evaluations of the probability as well as the consequences of a negative outcome." (Sjöberg et al. 2004 p. 8) The tendency to overestimate small probabilities has been widely discussed in the context of prospect theory (Kahneman and Tversky 1979; see also Barberis 2013).

likely that the perceived risks of an accident deviate from the objectively estimated probabilities and may play a weightier role in final decisions on licenses for new nuclear reactors, for example. Moreover, politicians' decisions may be influenced by their own risk perceptions, their views of their constituents' perceptions and the opinions of citizens or voters at large.[3]

We introduce an analytical framework for measuring the social costs of nuclear power resulting from perceived risks of a nuclear accident. Our investigation of risk perceptions reveals insights into their welfare consequences, which become capitalized in political decisions in licensing processes. In earlier work, Salanie and Treich (2009) have provided an economic rationale for over-regulation when risks are misperceived and citizens make choices according to their beliefs. 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.

Based on the welfare components identified in the analytical model, we measure perceived risks of nuclear accident using surveys targeting the general public in Finland. 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.[4] Moreover, one of the world's most keenly followed and latest reactor technologies, the European Pressurized Water Reactor (EPR), has been under construction in Finland for over ten years. As the media frequently reported the opinion polls on nuclear power conducted in connection with each vote in Parliament and, more recently, have covered delays in the start-up of energy production at the new reactor, the public is familiar with the issue of nuclear power. We investigate the extent to which the public's risk

[3] See, e.g., Levitt (1996), Lee et al. (2004), Washington (2008) and, for political decision making in environmental issues, Nelson (2002).
[4] According to the Finnish Nuclear Energy Act (11.12.1987/990), Parliament has to evaluate whether the use of nuclear energy, taking into account its various effects, is "in line with the overall good of society". In Finnish parliamentary politics, nuclear energy is what is known as an 'issue of conscience', in which voting outcomes often split along other than established party lines.

perceptions affect their stand on nuclear power and their stated behavior in a putative referendum on new reactor licenses.

Our empirical modelling draws on the extensive previous research on risk perceptions. There is a vast literature in cognitive psychology on risk 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 and perceptions in different domains and contexts (e.g., Harrison et al. 2007, Dohmen et al. 2011, 2012). A recent study has investigated the effect of the Fukushima nuclear accident on the risk perception of residents near a nuclear power plant in China (Huang et al. 2013). We measure perceptions of risks based on responses to multiple survey items eliciting perceived risks in the context of a referendum-type vote on nuclear power licenses and in the context of personal risks in everyday life. As we have responses to several risk questions and risk rating scales, we can observe the use of the risk scale in separate items by every individual and control for the risk perceptions when explaining preferences in voting.[5] We study the impacts of a set of demographics and risk perceptions on voting for or against license applications for new nuclear power reactors in Finland, and provide well-identified evidence on whether perceived risk or fear of accident affects voters' preferences. The survey vote on license applications was exactly the same as the vote in the Finnish Parliament in July 2010.

Obviously, those who oppose nuclear power are likely to perceive its risks high. This raises the concern of reverse causality.[6] We show that our results on the impacts on voting of perceived risks of a nuclear accident are robust to a series of specification checks. In particular, our instrumental variable estimation strengthens our confidence in perceived risk of accident being a strong determinant of respondents' voting decision. Moreover, we validate our model of hypothetical voting by analyzing the observed voting behavior of the members of Parliament who voted on the reactor licenses in Parliament in 2010. There, too, predicted perception of the risk of an accident turns out to be a statistically significant determinant of voting decision.

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[5] In fact, for a sample of the members of the Finnish Parliament we have observed stated risk perceptions and actual voting behavior in Parliament regarding licenses.

[6] A potential endogeneity bias has also been investigated by Riddel (2011) in her model of perceived mortality risk and acceptance of the risk associated with nuclear waste transport.

Finally, drawing on the survey data, we can estimate how important a factor risk perceptions are for calculations of the social costs of nuclear power. Our focus on risk perceptions is motivated by the fact that previous studies have shown rather low external costs in the case of a potential large-scale nuclear accident per produced MWh (e.g., Laes et al. 2011). Still, nuclear power continues to be a highly contested issue in energy policy. The growing literature on the long-term physical and psychological health effects of nuclear catastrophes on well-being (e.g., Almond et al. 2009, Danzer and Danzer 2016, Goebel et al. 2014) stresses the importance of analyzing the impacts of risk perceptions on the choices of technology in energy policy, where externalities and social costs play a crucial role. Our results show that risk perceptions increase the social costs of nuclear power considerably, and provide a case for policies that mitigate real risks and reduce fear. Although one should be cautious when drawing conclusions for other countries from the experience in Finland, we believe that the results of our study may significantly improve the understanding about the risk perceptions and their importance in the external costs associated with energy production and implications for policy making in other countries.

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 on the calculation of probabilities of nuclear accidents and elicitation of 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 results and section 6 puts forward a monetary estimate of the social cost of perceived accident risk and discusses its 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 civilian use, it has always been a highly polarized issue in politics. The related perceptions of risk capitalize in political decision making on licensing new reactors: If there is strong opposition among the public, decision makers are not willing to approve new licenses. To illuminate this issue, this section provides background on the energy policy regarding nuclear power and discusses the role that perceived risks of an accident play in relation to objective risk assessment.

2.1 Energy policy regarding nuclear power and the Finnish context

Before the accident at Fukushima 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 to the accident in Europe in energy policy was swift, particularly in Germany. The country immediately closed down 8 GW of nuclear capacity and passed a law phasing 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. When the Swedish Parliament overturned a ban on building new nuclear reactors (in force since 1980), one of the largest utilities in the European energy industry, Vattenfall, applied, in 2012, to replace two of its existing reactors with new ones. The plan was dropped because of a new government in 2014 and, instead, the company aims to extend years of operation for the oldest reactors by at least 50-60 years. In 2013, the UK announced its intention to award a contract to a French energy company to build a new nuclear reactor. There is currently a total of some 70 nuclear reactors under construction in the world; of these, 29 are in China and 11 in Russia (IAEA 2014).[7]

The nuclear industry has been struggling with ever-escalating construction costs (Davis 2012, Kessides 2012), and it is claimed that these cost increases are attributable in part to safety regulations.[8] Considering private costs alone, that is, not taking into account the social costs of nuclear power, the competitiveness of nuclear power is even considered "questionable" by Linares & Conchado (2013).[9]

Our empirical analysis builds upon experiences in Finland. Currently, the country has four nuclear reactors that have been operating since the late 1970s and early 1980s, providing about 32% of its electricity. The Nuclear Energy Act, passed in 1987, prescribes that 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. The reactor has been under construction since 2005,

[7] Worldwide there are about 440 nuclear reactors in operation, and about 150 permanently shut down (IAEA 2014).
[8] After the Three Mile Island accident, reforms were launched in emergency response planning, reactor operation training, human factors engineering and radiation protection, among other areas. After Chernobyl, third-generation reactors have been developed intensively. After 9/11, nuclear power plants must provide adequate protection in the event of an attack by an airplane. Since Fukushima, additional safety standards have been introduced by the EU and individual countries.
[9] This finding is supported by the decision of the UK government to guarantee a price for power from a nuclear plant to be built at Hinkley Point that was double the wholesale power price by the time of decision in 2013; the legality of such financial support alone is under investigation by the EU (European Voice 2013).

and still is. The building of the reactor was launched as a flagship project for two energy companies, the Finnish TVO and French Areva, and there is worldwide interest in its third-generation EPR technology. The facility was expected to be in operation in 2009, but the latest estimates are that operation will not start until 2018 at the earliest.[10]

Despite the heavy delays and increasing costs projected for the fifth reactor, the Finnish Parliament accepted licenses for two additional reactors in 2010 for two energy companies, TVO and Fennovoima. The votes in Parliament took place eight months before the accident at the Fukushima Daiichi Nuclear Plant. Yet, risks were widely discussed in debates before the parliamentary votes. Public debate preceding the actual vote focused on meeting the Finnish targets for cutting greenhouse gas emissions, the employment potential of the new plants, their influence on renewable energy investments, and safety issues. However, the vote was solely on additional nuclear capacity in electricity production, and no other energy production alternatives or policies were taken stand on.[11]

Whereas government experts may have clear quantitative definitions of risks based on objective data, the public often evaluate risks in very different ways (Loewenstein et al. 2001). However, little is known about the risk perceptions of either decision makers or the public with regard to energy production that were debated in public prior to the decision of the Finnish Parliament to support an increased supply of nuclear energy. We hypothesize that both the objective probabilities of accidents and risk perceptions play an important role in decision making, a role which we formalize in our model in section 3. The determination of both of these risk measures is challenging, yet crucial from a social point of view, for they add to the external costs of nuclear power and affect social welfare.

2.2 Risk of accident and perceptions of risk

The liability of nuclear power plant operators is limited and, as insurers of last resort, governments carry out risk assessments of nuclear safety. Risk assessment provides useful insights into insurability and the costs of a putative nuclear power accident. In the literature, limited liability as an implicit subsidy has been studied by Heyes and Heyes (2000) and, more generally, energy accidents and costs

[10] The reactor will provide about 12 TWh of electricity. The two companies, TVO and Areva, disagree about the cause of the delays and have sued each other for compensation in claims of about 2.5 billion euros each.

[11] The debate was related to self-sufficiency and energy saving as additional domestic nuclear capacity was seen to replace imports from Sweden and Russia. With hindsight, it is useful to know that domestic electricity consumption has decreased 6 % since 2010; the decrease corresponds to 23% of nuclear electricity production.

has been discussed by Sovacool (2008) and Felder (2009), among others. Probabilities of nuclear accidents have typically been estimated based on probabilistic risk assessments (PRA) or statistical analyses of historical data. Hofert and Wüthrich (2011) cite assessments reporting annual probabilities of $1 \cdot 10^{-6}$ for accidents with long-term health damage and of $1 \cdot 10^{-8}$ for accidents with high financial losses (exceeding 8 billion USD). Reviewing historical frequencies of nuclear accidents, Cochran (2011) provides a list of nuclear power reactors that have experienced fuel-damage or partial core-melt accidents and puts forward on this basis an estimated frequency of core-melt accidents of about one in 1,400 reactor-years. Escobar Rangel and Leveque (2013) point out a 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. All in all, the literature suggests that the estimated probabilities are small and, ultimately, there is a fundamental difficulty in communicating the meaning of an estimated probability of a large-scale accident (no matter how low) to decision makers and the public.

Indeed, the communication of risk information is a sensitive policy process (Viscusi et al. 1991). How scientific estimates of probabilities are perceived is reflected in concerns among the general public about nuclear accidents and their risks. In democratic societies, the importance of perceptions of risk in decision making is recognized; for example, Sjöberg et al. (2004) point out 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.

The challenge is how to measure risk perceptions. Economists have long eschewed 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 (also those related to nuclear energy) 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)

The limitations of inferring preferences from revealed behavior are pronounced when individuals do not make choices regarding policies; referenda cannot be held on every issue (see, e.g., Daniel et al. 2014). In particular, the investigation of psychological and economic explanations of decision making under uncertainty (e.g., Weber and Johnson 2009) has prompted economists as well to increase the use of survey data on beliefs and risk attitudes for estimation of preferences (see, e.g., Manski 2004, Dohmen et al. 2011, Allcott 2013). Recently, support for the use of self-reported risk attitudes elicited by surveys has been found by Lönnqvist et al. (2015). When comparing a self-reported questionnaire measure of risk with an incentivized lottery-choice task (Holt and Laury 2002), they found that the questionnaire measure was more stable in a repeated test and correlated with personality factors predicting risk-taking behavior as well as with observed risk-taking behavior in a laboratory experiment.[12]

Here, we use data collected in surveys 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. Moreover, to test the impact of framing, risk perception of accident was elicited also in the context of risks associated with everyday life. Before presenting the empirical analysis we describe the analytical framework underpinning our regressions and welfare estimates on social costs.

3. Simple model for estimation of social costs of perceived accident risk

We introduce a model describing public perceptions of accident risk, which in turn influence the social costs of nuclear energy production through 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. The probability of voting to accept a license for a nuclear reactor, p_f, depends on perceived risk of accident at a nuclear power plant, r, such that the decision of an individual as to whether he or she votes in support of or against nuclear power reactor licenses can be given a utility-theoretic interpretation.

[12] Personality is an external predictor of risk-taking behavior. According to Nicholson et al. (2005), risk taking is associated positively with extraversion and openness, and negatively with neuroticism, agreeableness and conscientiousness.

Social planner

The social planner maximizes the welfare of individuals and takes the utility and risk preferences reflected in the probability of their 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 perception of risk 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, $D(r)$, $D'(r) > 0$.

Taking into account the objective probability of an accident, $\bar{r}$, the net benefits of energy production (value of electricity) are $\pi_f(\bar{r}; K_0 + R)$ for old capacity, K_0, and a new reactor, R, and $\pi(\bar{r}; K_0)$ for capacity without an additional nuclear reactor. The net benefits are increasing with capacity, but decreasing with the probability of an accident that causes damage, and $\pi'_f(\bar{r}) < \pi'(\bar{r}) < 0$. Hence, the objective function of the social planner reflects the utility weights of citizens and the disutility of risk perceptions:

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

If perceptions of the risk of a nuclear accident are larger than the objective probabilities, that is, $r > \bar{r}$, the social planner may consider reducing exaggerated risk perceptions to improve welfare. This may be viewed as the social planner considering how much effort, a, with a cost function $c(a)$, should be expended to maximize welfare

$$W = p_f(r-a)\pi_f(\bar{r}\,; K_0 + R) + \left(1 - p_f(r-a)\right)\pi(\bar{r}; K_0) - D(r-a) - c(a) \quad (2)$$

with respect to efforts such that

$$\frac{\partial W}{\partial a} = -p'_f\pi_f + p'_f\pi + D' - c' = 0 \quad \text{or} \qquad c' = -p'_f[\pi_f(\bar{r}; K_0 + R) - \pi(\bar{r}; K_0)] + D'. \quad (3)$$

Equation (3) indicates that the marginal impact of higher perceived risk equals the decreased probability of voting for nuclear power, p'_f (<0), times the loss in expected net benefits of electricity production $[\pi_f(\cdot) - \pi(\cdot)]$ and the increased disutility of excessive perceived risk, D'. In other words, in evaluating the net benefits the social planner takes into account the expected damage caused by a potential accident and optimally adjusts the efforts to diminish perceived risks. If the estimated objective probability of an accident increases, less effort will be allocated to diminishing perceived risks.[13] The last term on the right-hand side can be estimated, for example, by hedonic pricing, to investigate whether risk perceptions are capitalized in the prices of housing close to nuclear reactors. Risk perceptions may intensify in debates about location of new nuclear power plants or after an accident at an existing plant (see, e.g., Fink and Stratmann 2015, Coulomb and Zylberberg 2016).

The purpose of the present paper is to estimate the first term on the right-hand side, in which risk perceptions are capitalized in voting behavior. We will discuss the net benefits of expected electricity production in more detail when we calculate and evaluate the social costs.[14] Before that, in the following, we show that the marginal impact of perceived risks on citizens' choice to favor or oppose new licenses for nuclear power is the parameter to be estimated from the citizens' preferences.

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:

$$U_{iR} = \propto_R + s'_i\beta_R + r'_i\rho_R + \varepsilon_R$$
$$U_{i0} = \propto_0 + s'_i\beta_0 + r'_i\rho_0 + \varepsilon_0, \qquad (4)$$

where U_{iR} and U_{i0} represent the *i*th individual's indirect utility associated with the choice whether to have additional reactor capacity, indicated by sub-index R, or not, 0. Rational behavior implies that voting in favor of a nuclear reactor is preferred if $U_{iR} > U_{i0}$, and against if $U_{iR} < U_{i0}$.

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[13] This intuitively appealing result can be shown by comparative statics of the first-order condition in equation (3) such that $\frac{da}{d\bar{r}} = \frac{p'_f(r-a)[\pi'_f(\bar{r}) - \pi'(\bar{r})]}{p''_f(r-a)[\pi_f - \pi] - D'' - c''} < 0$ when $p''_f < 0,\ D'' > 0, c'' > 0$.

[14] For simplicity, we assume that $\pi_f(\bar{r}; K_0 + R) = \tau \cdot (K_0 + R) - \bar{r}\delta \cdot (K_0 + R)$ and $\pi(\bar{r}; K_0) = \tau \cdot K_0 - \bar{r}\delta \cdot K_0$, where τ is a marginal value of electricity, and δ is a parameter capturing the extent of the external cost of an accident based on an objective probability estimated in previous risk assessments. In other words, the objective probability of an accident is the same for a new reactor as for existing capacity, and the marginal damage of an accident is constant.

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

$$p_f = p(U_{iR} > U_{i0}) = p[\varepsilon_{i0} - \varepsilon_{iR} < \alpha_R - \alpha_0 + s'_i(\beta_R - \beta_0) + r'_i(\rho_R - \rho_0)]$$
$$= F[(\alpha_R - \alpha_0) + s'_i(\beta_R - \beta_0) + r'_i(\rho_R - \rho_0)], \quad (5)$$

where F is the distribution function of $\varepsilon_{i0} - \varepsilon_{iR}$. Assuming that the errors follow a logistic distribution and denoting $\alpha = \alpha_R - \alpha_0,\ \beta = \beta_R - \beta_0,\ \rho = \rho_R - \rho_0$, we have a standard logit model $p_f = p(U_{iR} > U_{i0}) = 1/[1 + e^{\alpha + s_i'\beta + r_i'\rho}]$. The logarithm of odds ratios for favoring nuclear power can be expressed as a linear function of the explanatory variables chosen, or

$$ln\left(\frac{p_f}{1-p_f}\right) = \alpha + s_i'\beta + r_i'\rho. \quad (6)$$

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 apply logit and linear probability models for the voting decision. Thereafter, several approaches are adopted to check robustness, including an instrumental variable estimation.

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 focusing 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. A random sample of 1000 citizens between 18 and 75 years of age was sampled from the Population Register. A survey proper 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 three and five weeks after the first mailing). The survey achieved a reasonably high response rate of 52%.[15] The questionnaire consisted of thematically grouped questions presented in a logical order, starting with the energy consumption issues most familiar to the respondents, for example, and ending with questions on their socio-economic background. The most important parts of the survey for our analysis were those that included items regarding a putative vote on nuclear power and a set of questions on perceived risks. The voting response was queried in a referendum-type question 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(s)” 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 increased unemployment, reduced energy self-sufficiency, lowered competitiveness of the Finnish economy, an increase in greenhouse gases and nuclear waste, an accident at a nuclear power plant, impacts on health of fine particles generated in energy production, the increased land area required for production of bioenergy and 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 wordings of the items eliciting risk perceptions are given in Appendix A (item from the survey proper) and Appendix B (items from the sub-samples).

4.2 Descriptive statistics

Table 1 shows the summary statistics of the data from the survey proper. 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).

[15] To investigate the stability of risk preferences, a similarly designed survey was carried out in September-November 2014. A sub-sample from this survey is utilized in section 5.3 for comparison purposes to investigate the impact of framing and psychometric scale of risk rating on the stated risk perceptions. The second survey achieved a response rate of 44% by contacting the respondents twice after the first delivery.

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 as we are interested in the marginal impact of additional capacity. Licenses for nuclear power were supported by 49% of the citizen respondents (row indicating ‘Voting’ in Table 1). This is lower than the proportion of MPs supporting nuclear power in the actual vote, which was 66%. However, opinion polls carried out and published prior to the vote suggest that there might have been a much closer vote in Parliament, as about 50% of the general public supported nuclear power in the polls (Energiateollisuus 2010).

To check the robustness of the results to non-response, a telephone follow-up survey was conducted for a sample of 100 non-respondents; the response rate was 50% with a slight overrepresentation of male respondents (66%). About 54% would have voted in favor of nuclear power. The most frequently mentioned reasons for non-response were lack of time, the survey being too long and the like; these were cited by about 75% of respondents, whereas lack of interest in the topic of the survey was cited by about 25% of respondents. The latter group is the most important as regards participation and self-selection in the sample. Among this group, 50% would have voted in favor of nuclear power. This finding counters a hypothesis that self-selection due to the topic was the driving force in responding to the survey.

Table 1 shows that age and distance to the nearest nuclear power plant (km) are continuous explanatory variables. The average age of the citizen respondents, 51 years, is higher than the average of the Finnish population at large (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% women and 50% men, which equals the proportion of males in the Finnish population at large (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 5,200 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 the means of responses for each risk perception queried. The risk of nuclear waste has the highest mean, followed by risk of accident, whereas the risk of increased unemployment yields the lowest mean. Failure in saving energy 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 the mean of the responses to all questions on perceived risks, 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 perceptions and risk behavior by gender. In particular, women typically report perceiving a higher risk of negative consequences than do men (see, e.g., Weber et al. 2002, Harris et al. 2006, Croson and Gneezy 2009, Coppola 2014 for gender differences in risk behavior).

5. Results

5.1 Determinants of risk perceptions

Ultimately, we are interested in assessing the impact of a perceived risk of accident at a nuclear power plant on the public opinion on new 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 querying the perceived risk of an accident on socioeconomic characteristics such as gender, age, education and income. We also include dummy variables for the status of being unemployed or an entrepreneur as explanatory variables. Moreover, by including the parliamentary constituencies as dummies we can control for regional fixed effects.[16]

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[16] Finland is divided into 13 constituencies for purposes of parliamentary elections. In our estimations, the constituency of Helsinki is used as a baseline category, and the constituency dummies (in roman numerals) run from south (I) to north (XI). We have excluded from our survey one constituency, the Åland Islands, which have an autonomous status under the Finnish Constitution. Hence, the actual number of constituency dummies is eleven.

Table 2 reports the results for linear regressions on the determinants of risk perceptions across two contexts. The primary determinants of risk perceptions regarding a power plant accident elicited in the context of general energy policy are reported in column (1). Male gender, high education and income have a statistically significant and decreasing impact on these perceptions. Gender has the strongest impact on the perceived risk of 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 presented separately for men and women. About 27% of men consider the risk of an accident to be 'high' or 'fairly high', whereas the corresponding proportion among women is twice as high, or 53%.

To investigate the framing of the item eliciting the perceived risk of accident (Appendix A), we present results for stated risk perception of accident elicited in the context of the respondent's everyday life (Appendix B, B2) in column (2). The statistically significant coefficients in columns (1) and (2) in Table 2 are strikingly similar, independent of framing. In the framing of personal risks, the age variable becomes statistically significant.

Moreover, we present regressions for two summary indicators on risk perceptions as dependent variables. One, "Average risk perception" is calculated as an average of the responses to the entire battery of questions regarding risks associated with energy policy (column 3). The other, in column (4) includes the average of all responses to risk perceptions elicited in the context of everyday life (item B2 in Appendix B). For average risk perceptions, we detect a similar tendency among men 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 income variable is negative and statistically significant for both summary indicators of risk perceptions.

Furthermore, we carried out separate linear regressions for the responses to all the questions eliciting risk perceptions in Appendix A; the results are reported in Table C1 in Appendix C. The regressions suggest that age and male gender have a statistically significant and negative impact as regards the perceived risk from greenhouse gases, fine particles, and failing to save energy. An interesting detail, one increasing the credibility of the context-specific and self-reported risk perceptions, is that an increase in unemployment is perceived as a greater risk by those who indicated that they were unemployed at the time of the survey (second column in Table C1); the impact is statistically significant.

Finally, Table 3 shows the correlations between the stated risk perceptions for the general context of energy policy (upper panel) and the context of everyday life (lower panel). 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 fine particles from burning fossil fuels. For our analysis, the most important correlations are those relating to the perceived 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 fine particles. We 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 reactors

We now proceed to 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 on a scale from 1 to 5, the marginal impact of that perception denotes a change from one risk category to the next on the five-point scale. We investigate the impact on the results of the rating scale and the length of scale used in the risk assessments in section 5.3.

We are especially interested in the impact of the perceived risk of accident on voting. To gain insight into the relative impact of a perceived accident risk as compared to 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 perceived risk of accident by subtracting from it average risk perception calculated without including perceived risk of accident. 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 risk of accident - 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 accident risk in the regression reported in column (3), perceived risk of accident 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 average risk excluding accident risk. The covariate (monthly household gross) income is statistically significant in all models.

5.3 Robustness and alternative modeling approaches

Perceptions of risk in general, and of the risk of an accident in particular - our principal interest 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 (and distance to the nearest nuclear power plant in km in columns 5-8) 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 of Table 5, the results are reported for specifications with an alternative indicator variable that scales the perception of accident risk ('accident risk scaled'). Scaling of 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. The coefficient captures the impact of the extent to which the respondent's perception of accident risk deviates from 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), but still strongly statistically significant.

In columns (3) and (4), accident risk is measured with two dummy variables. The first receives a value of one if the respondent has chosen the ‘cannot say’ option (Accident risk=3 on the Likert scale); the second takes on a value of one if the risk on an accident 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 with relatively high stated perceived risk on the other. 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 reactors considerably, or over 40%. The probability decreases also when the respondent has indicated ambiguity regarding the risk of accident by choosing ‘cannot say’ (the midpoint, or value of 3, on the Likert scale).[17] The coefficients for the two risk dummies are statistically significant.

Finally, the impact on voting of framing and scaling of risk rating question voting was investigated. Instead of five-point scale, rating from 0 to 10 was used for elicitation of risk perception of accident in the context of risks in everyday life (item B3 in Appendix B). Again, the accident risk is strongly statistically significant, and the absolute magnitude of the coefficient reflects the dense scale of 0-10 used (reported in column 7). Transforming the 11-point scale back to 5-point scale generates a larger coefficient in column (8) which is consistent with the other accident risk coefficients in Table 5.[18]

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

[17] We also carried out regressions in which we had a separate dummy for each level of risk perception. Moreover, for additional regressions, we interpreted the midpoint, ‘cannot say’, as a missing observation, and then recoded the rest of the risk perceptions on a 4-point scale (low, fairly low, fairly high and high). In all these alternative estimations, the coefficients for the recoded perceptions of accident risk turned out to be negative, statistically significant and in line with the results shown in Table 5. (The results are not shown here; available upon request.)

[18] In rescaling, initial risk ratings in categories 0-1 were transformed to 1 and, accordingly, ratings of 2-3 to 2, 4-6 to 3, 7-8 to 4 and 9-10 to 5. See Coppola (2014, Appendix, Table A1).

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, omitted variables bias and reverse causality

Our findings suggest that a perceived risk of accident indeed matters 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 self-reported perceptions of the risk. Clearly, 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), in fact orders of magnitude smaller than a 'high' perceived risk. Indeed, it is likely that the citizens are considering not only the risk of an accident but also its potential detrimental consequences. Findings in psychology suggest that overweighting of small probabilities is common for outcomes that evoke strong emotions (Loewenstein et al. 2001). Hence, we should treat the perceptions as indicators that are compromised by measurement errors. A second concern is reverse causality, which arises in our welfare analysis as estimates are based on stated perceived risks and intended behavior regarding the voting decision (Riddel 2011). We address these problems below adding control variables associated with risk perceptions and using instrumental variables.

As stated by Angrist and Krueger (2001) a good instrument is correlated with the endogenous regressor for reasons the researcher can verify and explain, but uncorrelated with the outcome variable for reasons beyond its effect on the endogenous regressor. It is notoriously difficult to find such a variable. Angrist and Pischke (2009, 117) suggest that good instruments come from combination of institutional knowledge and ideas about the process determining the variable of interest.

Previous research suggests that objective probabilities are good candidates as instruments for subjective, or perceived, risks. However, for obvious reasons, an estimated 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, that is, Chernobyl in 1986 and Fukushima in 2011. The occurrence of these two accidents (classified in the highest severity category on a 7-point scale) is exogenous to the respondents, and we exploit this fact in creating our instruments. The literature suggests that world-views and attitudes are influenced by dramatic events in young adulthood in particular. Events that register most strongly in early adulthood have the advantage of primacy, which gives them an especially strong role in impression formation (Schuman and Scott 1989). To account for these effects, 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 the age by which about 90% of the cohort have moved out of their childhood home and no longer live 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 (Statistics Finland 2012). Hence, we have two dummies, one for those who were between 22 and 26 years of age at the time of Fukushima, the other for those who were between 26 and 30 years of age at the time of Chernobyl.

Our second instrument is based on responses to a survey item eliciting the perceived health risk caused by fine 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 their voting decision: Only 1.5% of respondents indicated that fine particles were a significant consideration. Therefore, we hypothesize that the variable captures general environmental attitudes of the respondents, attitudes that prevail when they consider all of the other risks. Still, we are aware of the concern that the variable may affect the outcome variable in spite of the respondents' stated unimportance of the factor. Hence, the perception of accident risk is instrumented by two age-group dummies and by the perceived health risk of fine particles.

The first two columns in Table 6 show the results of OLS estimations with additional covariates, "Entrepreneur" and "Unemployed". In particular, in the first column we have included the risk perception of nuclear waste that the respondents indicated in the survey as an explanatory variable. Of course, nuclear waste risk is heavily correlated with the perception of accident risk, but we would like to see whether the variable fades out the impact of accident risk. This is not the case. The coefficient for accident risk is statistically significant and in the range of estimates in Table 5. This is true also for column (2) where average risk excluding accident risk (i.e., average of responses to all items eliciting risk perceptions, with the exception of accident risk) is included as covariate.

Table 6 shows the results of a second stage of 2SLS in columns (3) and (4), and the lowermost part of the table reports the coefficients for the instruments used in the first stage. Accident risk remains statistically significant in all model variants. When the perceived risk of accident is instrumented, the coefficient for accident risk is even larger than the largest marginal impact in the previous logit and OLS models (Table 5). However, the instrument may affect directly the voting decision. All the instruments are strongly correlated with the endogenous regressor, and F-test statistics are reasonably high for the instruments. The results strengthen our confidence in perceived risk of accident being a strong determinant of respondents' voting decision.

All in all, the coefficients for the perceived risk of accident are negative and in the same order of magnitude as in the corresponding models in Table 5 both when additional covariates are included in OLS estimation and when instrumental variables are used.

5.5 Behavioral validity and hypothetical voting

Thus far, we have shown that risk perceptions have a substantial impact on voting on nuclear power. However, we have not been able to observe actual voting behavior for the simple reason that there has not been a referendum on nuclear power in Finland similar to that held in some other European countries. As Daniel et al. (2014) note, however, even a direct vote would not reveal preferences, because voters lack full information about the consequences of alternative policy options.

To ascertain whether prevailing risk perceptions have explanatory power for observed voting on nuclear energy, we analyze the actual vote on nuclear power permits in the Finnish Parliament in 2010. For a small sub-sample of the members of Parliament (N=44), we have data on stated risk perceptions, elicited in a separate survey carried out in January-February 2011, about half a year after the actual vote. We include these observations in the data set, and regress the perceived accident risk on demographics and a dummy variable for MP. The results in Table 7 show that MPs indicate a lower perceived risk than citizens do, but the coefficient for MP2010 is not statistically significant. Using this regression we predict the perception of accident risk for MPs who voted on licenses in 2010 (N=190). Then we run the same regression as in Table 5, column (6), but include MPs in the data set using their stated or predicted perception of accident risk as covariates[19]. As shown in Table 8 columns (1) and (2),

[19] We do not have data on MPs' monthly household gross income.

the coefficient for a dummy variable for MP is small, and it is not statistically significant in the voting decision, whereas the risk perception is negative and statistically significant. Using the OLS models for predicting voting probabilities, we find that the predicted probability of voting for nuclear power licenses is 50% for the citizens surveyed and 64% for the MPs who actually voted in Parliament. Recall that 66% voted for licenses in Parliament in 2010. Further, we carried out a similar IV regression as for the citizens using age dummies as instruments. Again, the coefficient for risk perception turned out negative, and statistically significant as shown in Table 8 column (3). From this model, the predicted probability of voting for nuclear power licenses is 64% for the MPs. Overall, we take these estimations as additional evidence that the risk perceptions of accident play an important role in explaining preferences for nuclear power plant licenses not only in the citizen survey voting but in actual voting as well.

6. Monetary evaluation of the social cost of perception of risk of accident

It seems evident that the marginal impact of perceiving the risk of accident as high is large and considerably reduces a person's willingness to support licenses for new nuclear reactors. Using the estimated marginal impacts of the perceived risk of accident 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 loss of expected electricity production was derived to be $-p_f'\left[\pi_f(\cdot) - \pi(\cdot)\right]$ in equation (3). We have estimated the coefficient for the perceived risk of an accident, or the marginal impact of increased perceived risk on voting probability, p_f'. To compute the total monetary value of the loss of expected electricity production, we need an estimate of $\left[\pi_f(\cdot) - \pi(\cdot)\right]$, which is the increase in the net benefits of the electricity production at stake in a vote on licenses. In other words, the total welfare loss is an external cost of risk, which is an opportunity cost, or, as we interpret it, a willingness to pay for not having more nuclear power due to the perceived risk of an accident.

Recalling from section 3, the net benefits of the electricity produced by nuclear power consist of the value of electricity generated less the expected cost of an accident. Hence, for a given objective probability of an accident, $\bar{r}$, the net benefits of an additional reactor generating electricity, R, can be formulated as $\pi_f(\cdot) - \pi(\cdot) = (\tau - \bar{r}\delta)R$, where τ is a marginal value of electricity, and δ is a parameter capturing the extent of the external cost of accident based on an estimated objective probability.[20]

The marginal value of nuclear electricity can be related to its projected generation costs which have been estimated by the OECD (2010) at 30–70 euros/MWh for new reactors. One must then subtract from this the expected value of the cost of an accident, which is obtained by multiplying the total cost of the accident by the probability of its occurrence (expressed per reactor-year). Scientific estimates on the probabilities of accidents are discussed in the literature (see section 2.2) and so are the total costs of consequences of an accident. In a recent synthesis study for the European Commission, D'haeseleer (2013) suggests that "a reasonable order of magnitude value" of the external cost due to nuclear accidents is 1 euro/MWh.[21]

Using the marginal impact of perceptions of accident risks from the previous models (Tables 5 and 6) and assuming the marginal value of electricity to be 30 euros/MWh and the external cost of an accident to be 1 euro/MWh , a back-of-the-envelope calculation indicates that the cost of perceived risk of an accident ranges from 3 to 7 euros per MWh.[22] Hence, even our lowest estimate of that cost is more than three times that of previous estimates based on the objective risks, or estimated probabilities of accidents (as discussed in Laes et al. 2011 and above).

The considerable discrepancy between the social cost of risk perceptions capitalized in voting behavior and the previously estimated external costs of accident risks suggests that perceived risks should not be underestimated in energy policy. As the perceptions 'fairly high' or 'high' risk of nuclear accident expressed in our survey are widely held among the public, decision makers may take an interest in investing in measures to reduce anxiety regarding the risks and thereby increase welfare. This finding may also explain, and justify, the strong reactions of regulators and policy makers following the major

[20] For simplicity, we assume that $\pi_f = \tau \cdot (K_0 + R) - \bar{r}\delta \cdot (K_0 + R)$ and $\pi = \tau \cdot K_0 - \bar{r}\delta \cdot K_0$.

[21] The cost estimate is based on his extensive literature review, but D'haeseleer underlines that more research on the subject is "highly desirable". As range of uncertainty for the cost estimate, he applies a rule of thumb, taking 1/3 as lower bound and x 3 as upper bound, or 0.3-3€/MWh.

[22] For the lowest coefficient, -0.102, we have 0.102·(30 €/MWh-1€/MWh)=3.0 €/MWh and, for the highest, -0.246, we have 0.246·(30 €/MWh-1€/MWh)=7.1 €/MWh.

nuclear power plant accidents: Their responses have been a means of reducing not only the probability of a new accident, but also fear among the public.

7. Conclusions

Drawing on Finnish survey data on the risk perceptions of the general public in the context of a referendum-type vote on permits for nuclear power, we show that risk perceptions affect voting behavior. Various model specifications show that an estimated high perceived risk of nuclear accident decreases considerably the probability of voting in favor 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 statements of perceived risks are extremely high compared to the scientifically estimated probabilities of accidents.

Our results indicate that women in particular perceive the risk of a nuclear accident as high, even after controlling for education. Indeed, the discrepancy in risk perceptions between men and women may not reflect differences in education or rationality, for a similar discrepancy has been found among men and women scientists who have considerable knowledge of risk assessment procedures (e.g., Barke et al. 1997). Interestingly, Finucane et al. (2010) suggest that risk perceptions may be related to individuals' levels of decision-making power, but they also underline that there is variation across individuals regarding their sociopolitical attitudes and associated risk perceptions. In future research, comparison of the risk perceptions of citizens and MPs regarding nuclear power would be useful, as the latter group should be better informed about the risks.

Ascertaining and understanding people's risk perceptions can help to reduce expenditures and disutility from uncertainty and to improve risk management and social welfare. Yet, as Lowenstein et al. (2001) note, there is very little research on fear-reduction strategies that might be effective at the societal level. Educating the public about risks and risk assessment in the case of nuclear power may still fail to move public opinion to coincide with the views of experts. Both regulatory controls and political risks are likely to affect the revenues from, costs of and financing conditions for nuclear power in the future. We have shown that the magnitude of these welfare costs may be high.

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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	0.48	0	1	190
Demographics											
Age	50.99	15.21	18	76	508	42	51.54	10.26	28	72	199
Male	0.50	0.50	0	1	509	0.49	0.60	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	0.41	0	1	495	0.20	1	0	1	1	199
Entrepreneur	0.06	0.24	0	1	506	0.10	0.15		0	1	199
Unemployed	0.06	0.23	0	1	506	0.08					
Income (euro/mo)	3925	2111	1500	8700	495						
Distance to nearest nuclear power plant (km)	187.8	166.4	15.1	896.2	516		177.8	157.7	16.3	896.2	187
Constituencies											
I	0.08	0.28	0	1	518		0.12	0.32	0	1	198
II	0.15	0.36	0	1	518		0.16	0.37	0	1	198
III	0.07	0.26	0	1	518		0.08	0.27	0	1	198
IV	0.05	0.22	0	1	518		0.05	0.21	0	1	198
V	0.08	0.27	0	1	518		0.07	0.26	0	1	198
VI	0.10	0.30	0	1	518		0.09	0.29	0	1	198
VII	0.08	0.28	0	1	518		0.09	0.29	0	1	198
VIII	0.08	0.27	0	1	518		0.08	0.27	0	1	198
IX	0.08	0.27	0	1	518		0.09	0.28	0	1	198
X	0.06	0.23	0	1	518		0.05	0.22	0	1	198
XI	0.10	0.30	0	1	518		0.09	0.29	0	1	198
XII	0.06	0.23	0	1	518		0.04	0.18	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 of perceived accident risk and alternative summary indicators of risk perceptions by sample

	Accident risk perception[1)]		Average risk perception[1)]	
Framing of risk rating	General[2)] energy policy (1)	Personal[3)] everyday life (2)	General[2)] energy policy (3)	Personal[3)] everyday life (4)
Age	0.006	0.011*	-0.003	0.008**
	(0.004)	(0.006)	(0.002)	(0.004)
Male	-0.705***	-0.752***	-0.255***	-0.196*
	(0.130)	(0.174)	(0.064)	(0.110)
High education	-0.438***	-0.406**	-0.094	0.012
	(0.159)	(0.205)	(0.079)	(0.131)
Income	-0.083**	-0.135***	-0.061***	-0.061**
	(0.031)	(0.043)	(0.015)	(0.027)
Entrepreneur	-0.092	-0.145	-0.126	0.145
	(0.260)	(0.363)	(0.129)	(0.226)
Unemployed	0.055	0.262	-0.057	-0.324
	(0.287)	(0.321)	(0.138)	(0.205)
Constituencies	yes	yes	yes	yes
Constant	3.204***	2.834***	3.410***	2.882***
	(0.363)	(0.492)	(0.180)	(0.311)
N	478	215	484	206

1) Measured on Likert scale 1-5

2) The exact wording used for elicitation of risk perception is given in Appendix A.

3) The exact wording used for elicitation of risk perception is given in B2 (Q.10.) of Appendix B.

Table 3. Correlations between risk perceptions (general energy policy, Appendix A), N=472

	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

Correlations between risk perceptions (personal everyday life, Appendix B, item B2, N=213)

	Nuclear accident	Burglary	Transport accident	Fire	Heart attack	Car accident	Struck by lightning	Average risk
Nuclear accident	1.0000							
Burglary	0.0634	1.0000						
Transport accident	0.5105	0.2398	1.0000					
Fire	0.3218	0.3055	0.4093	1.0000				
Heart attack	0.1847	0.2622	0.2315	0.4135	1.0000			
Car accident	0.2272	0.3578	0.2356	0.5491	0.4864	1.0000		
Struck by lightning	0.0634	1.0000	0.2398	0.3055	0.2622	0.3578	1.0000	
Average risk perception	0.5402	0.6902	0.6302	0.7149	0.6224	0.6983	0.6902	1.0000

Table 4. Risk perceptions and voting on nuclear power

Dependent variable:	Voting on nuclear power (1=in favor, 0=against)		
	(1)	(2)	(3)
Age	0.004*** (0.001)	0.003** (0.001)	0.005*** (0.001)
Male	0.218*** (0.040)	0.300*** (0.044)	0.253*** (0.042)
High education	0.010 (0.048)	0.080 (0.054)	0.033 (0.051)
Income	0.021** (0.009)	0.025** (0.011)	0.026*** (0.010)
Accident risk (1–5)	-0.144*** (0.014)		
Average risk excluding accident risk (1-5) [1)]		-0.083*** (0.033)	
Accident risk scaled[2)] (-3.5 – 3.4)			-0.125*** (0.015)
Constant	0.499*** (0.096)	0.299*** (0.143)	0.025 (0.083)
Number of observations	479	452	450
Adjusted R^2	0.29	0.14	0.24

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

OLS regression coefficient estimates; standard errors in parentheses; ***, **, * indicate significance at 1-, 5-, and 10-percent level, respectively.

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

Variable							Personal risk in everyday life	
	Logit (1)	OLS (2)	Logit (3)	OLS (4)	Logit (5)	OLS (6)	Scale 0-10 OLS (7)	Rescaled 1-5 OLS (8)
Age	0.008*** (0.002)	0.006*** (0.001)	0.007*** (0.002)	0.005*** (0.001)	0.007*** (0.002)	0.005*** (0.001)	-0.0005 (0.0029)	-0.0005 (0.0029)
Male	0.296*** (0.052)	0.246*** (0.044)	0.267*** (0.053)	0.203*** (0.041)	0.267*** (0.053)	0.210*** (0.042)	0.176** (0.089)	0.188** (0.087)
High education	0.041 (0.072)	0.035 (0.053)	0.026 (0.072)	0.022 (0.049)	0.008 (0.071)	0.013 (0.050)	0.010 (0.114)	-0.023 (0.115)
Income	0.039*** (0.014)	0.028** (0.010)	0.030** (0.014)	0.020** (0.010)	0.031** (0.014)	0.022** (0.010)	0.002 (0.023)	0.004 (0.023)
Accident risk scaled (-3.5-3.4)[1)]	-0.164*** (0.023)	-0.127*** (0.016)						
Accident risk=3			-0.341*** (0.062)	-0.323*** (0.074)				
Accident risk=4 or 5			-0.508*** (0.046)	-0.452*** (0.043)				
Accident risk (1-5)					*-0.184*** (0.022)*	*-0.143*** (0.015)*	*-0.085*** (0.014)*	*-0.197*** (0.032)*
Constant		-0.083 (0.119)		0.247** (0.113)		0.432*** (0.125)	0.768*** (0.250)	0.919*** (0.259)
Distance to nearest nuclear power plant	no	no	no	no	yes	yes	yes	yes
Constituencies (dummies I-XII)	yes	yes	yes	yes	yes	yes	yes	yes
Number of observations	450	450	479	479	478	478	113	113
R^2	0.21	0.24	0.26	0.30	0.25	0.28	0.30	0.30

1) Average risk excluding accident risk (i.e. average of responses to all items eliciting risk perceptions but accident risk) is subtracted from accident risk.
Standard errors in parentheses; ***, **, * indicate significance at 1%, 5%, and 10% level, respectively.

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

Dependent variable:	Voting on nuclear power (1=in favor, 0=against)			
Endogenous variable:			Accident risk	
	OLS		IV, 2nd stage[1)]	
Variable	(1)	(2)	(3)	(4)
Accident risk	-0.110***	-0.142***	-0.125*	-0.246***
	(0.019)	(0.016)	(0.074)	(0.043)
Nuclear waste risk	-0.056***			
	(0.020)			
Average risk excluding accident risk [2)]		-0.012		
		(0.032)		
Age	0.004***	0.004***	0.004***	0.005***
	(0.001)	(0.001)	(0.001)	(0.001)
Male	0.215***	0.216***	0.234***	0.143***
	(0.042)	(0.044)	(0.068)	(0.053)
High education	0.018	0.041	0.040	-0.020
	(0.050)	(0.052)	(0.061)	(0.055)
Entrepreneur	-0.064	-0.038	-0.051*	-0.063
	(0.081)	(0.084)	(0.081)	(0.085)
Unemployed	-0.037	-0.036	-0.052	-0.037
	(0.091)	(0.095)	(0.089)	(0.094)
Distance to nearest nuclear power plant	-0.0002	-0.0005	-0.0001	0.0000
	(0.0005)	(0.0005)	(0.0005)	(0.0005)
Constant	0.721	0.594***	0.533**	0.860***
	(0.125)	(0.149)	(0.229)	(0.163)
Constituencies	yes	yes	yes	yes
1st stage for accident risk:				
Fukushima (age dummy)			0.830***	
			(0.302)	
Chernobyl (age dummy)			0.691***	
			(0.204)	
Fine particles (risk 1-5)				0.400***
				(0.050)
F-test for instruments			8.94	64.93
N	484	455	486	481

1) Instruments used: column (3) dummies for accidents in young adulthood and column (4) risk of fine particles and health impairment due to burning of fossil fuels
2) Average risk, excluding accident risk, i.e., average of responses to all items eliciting risk perceptions, with the exception of accident risk (for these 8 items eliciting risk perceptions, see Appendix A)

Table 7. Primary determinants for perceived accident risk
(Pooled sample of citizens and members of Parliament in 2010)

Variable	Accident risk perception[1)]
Age (years)	0.006 (0.004)
Male	-0.683*** (0.121)
High education	-0.365*** (0.146)
High income	-0.168 (0.153)
MP 2010 (dummy)	-0.270 (0.252)
Constant	3.031*** (0.236)
N	524

1) Measured on Likert scale 1-5

OLS regression coefficient estimates; standard errors in parentheses; ***, **, * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 8. OLS and IV estimation of the impact on voting of a perceived risk of nuclear accident.

Dependent variable:	Voting on nuclear power (in favor=1, against=0)		
	OLS		IV, 2nd stage[2)]
Variable	(1)	(2)	(3)
Accident risk	-0.102*** (0.019)	-0.137*** (0.015)	-0.141 (0.091)
Nuclear waste risk	-0.059*** (0.019)		
Average risk excluding accident risk[1)]		-0.023 (0.031)	
Age	0.003*** (0.001)	0.004*** (0.001)	0.004*** (0.001)
Male	0.162*** (0.037)	0.165*** (0.037)	0.169** (0.072)
High education	0.030 (0.041)	0.034 (0.041)	0.035 (0.055)
Distance to nearest nuclear power plant	-0.0002 (0.0004)	-0.0001 (0.0004)	-0.0001 (0.0004)
MP 2010	0.017 (0.043)	0.034 (0.046)	0.021 (0.054)
Constant	0.727*** (0.112)	0.647*** (0.134)	0.595** (0.267)
Constituencies	yes	yes	yes
1st stage for accident risk Fukushima (age dummy)			0.722*** (0.263)
Chernobyl (age dummy)			0.448*** (0.148)
F-test for instruments			8.00
N	676	674	676

1) Average risk, excluding accident risk, i.e., average of responses to all items eliciting risk perceptions, with the exception of accident risk (for these 8 items eliciting risk perceptions, see Appendix A)
2) Instruments used: Dummies for accidents in young adulthood

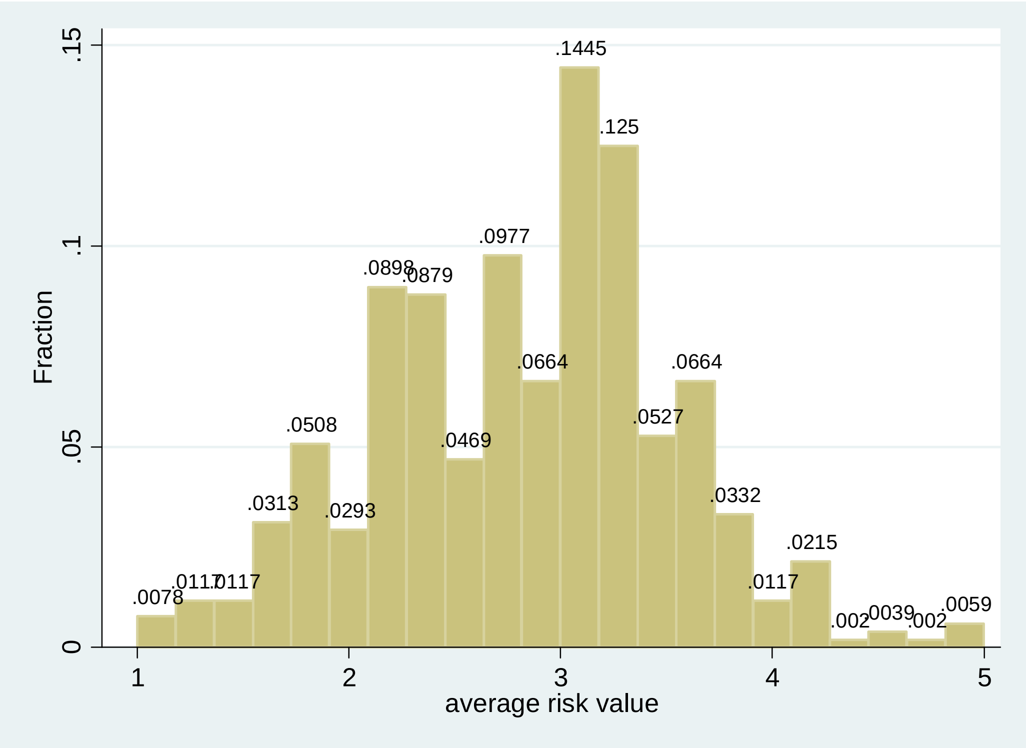

Figure 1 a. Histogram of elicited risk perceptions, average of nine risk evaluations (measured on a five-point scale 1= low risk; 5=high risk)

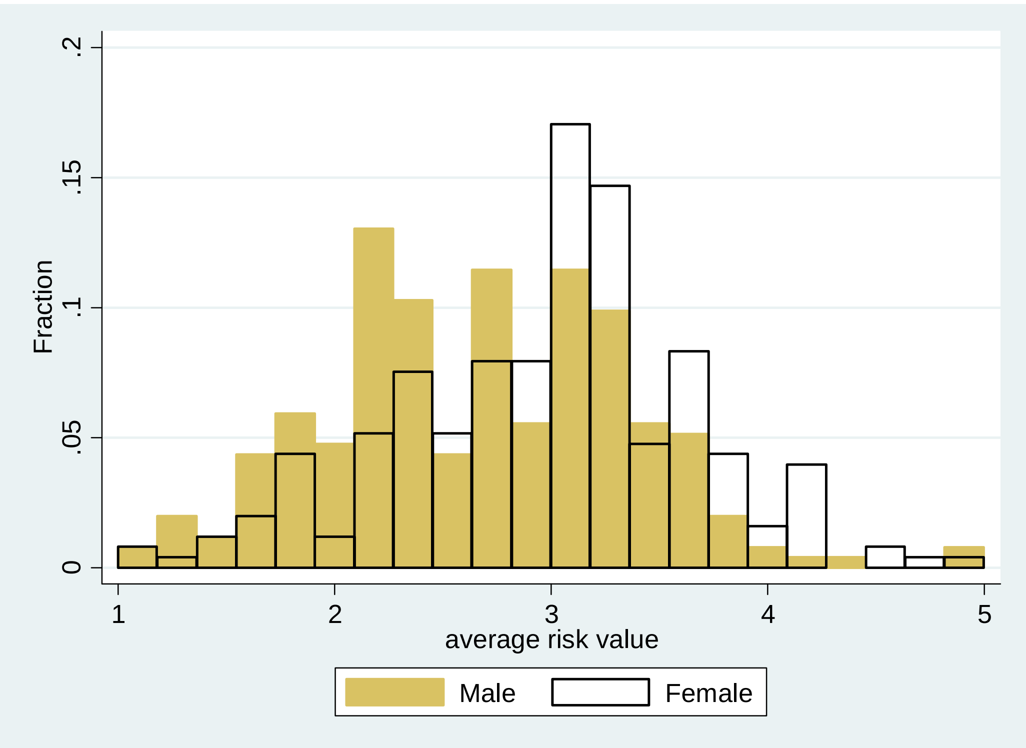

Figure 1 b. Histogram of elicited risk perceptions by gender, average of nine risk evaluations (measured on a five-point scale 1= low risk; 5=high risk)

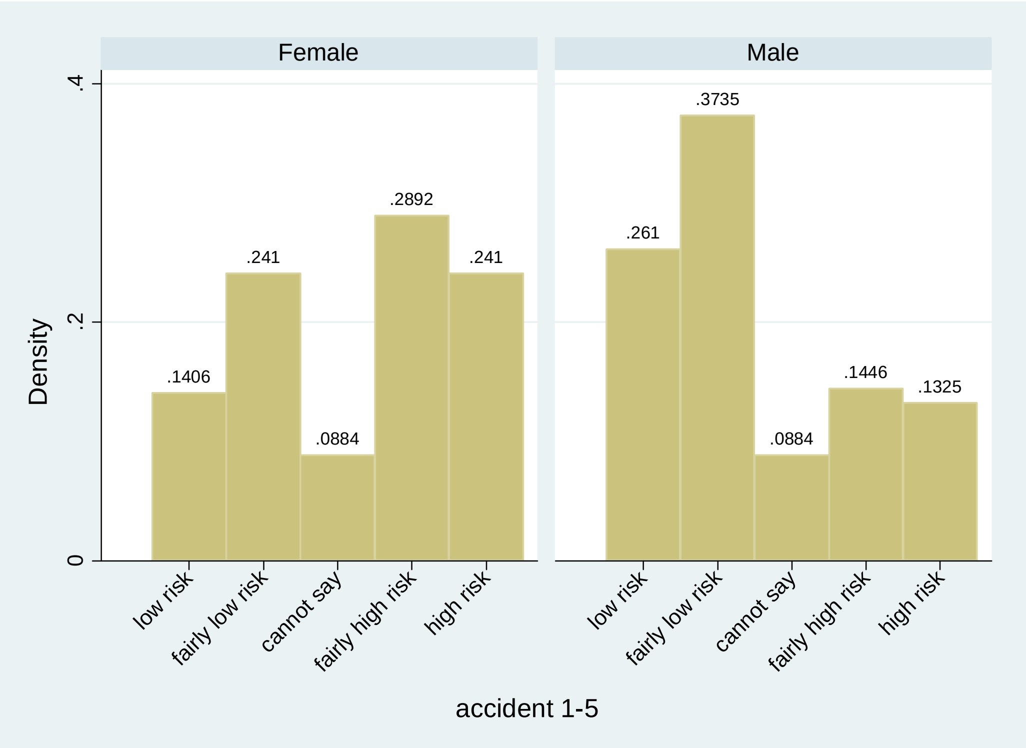

Figure 2. Histograms of responses by gender on item querying perceived risk of accident at nuclear power plant

Appendix A Survey item eliciting risk perceptions

Q.7. Consider your vote regarding additional nuclear reactor. In your opinion, how significant are the following risks for Finland?

Provide a risk rating from 1 to 5 such that 1=low risk, ..., 5=high risk. Please utilize the whole scale from one to five when applicable. On each row below, check the rating that best reflects your view.

	Low risk	Fairly low risk	Cannot say	Fairly high risk	High risk
	1	2	3	4	5
Increased unemployment	☐	☐	☐	☐	☐
Decreased energy self-sufficiency	☐	☐	☐	☐	☐
Increased greenhouse gases	☐	☐	☐	☐	☐
Radioactive nuclear waste	☐	☐	☐	☐	☐
Lowered competitiveness of the economy	☐	☐	☐	☐	☐
Fine particles in energy production that impair health	☐	☐	☐	☐	☐
Bioenergy production taking land from food production	☐	☐	☐	☐	☐
Accident at nuclear power plant	☐	☐	☐	☐	☐
Failure in saving energy	☐	☐	☐	☐	☐

Appendix B Items eliciting risk perceptions included in the survey sub-samples

B1. This sub-sample included an item described in Appendix A (Question 7.), but the rating for each risk perception was given on a scale from 0 to10. Visual illustration for accident risk as follows:

Q.7. … In your opinion, how significant are the following risks for Finland?

Provide a risk rating from 0 to 10 such that 0=no risk at all, …, 10=very high risk.

	No risk at all										Very high risk
	0	1	2	3	4	5	6	7	8	9	10
Accident at nuclear power plant	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

B2. This sub-sample included a similar item as described in Appendix A (Question 7.), and an additional item eliciting risk perceptions in everyday life (Question 10.):

Q.10. Our everyday life involves many kinds of risks. In the following, we ask you to evaluate how threatening you perceive the following risks. Please check the rating that best reflects your opinion.

	Low risk	Fairly low risk	Cannot say	Fairly high risk	High risk
	1	2	3	4	5
Burglary	☐	☐	☐	☐	☐
Transport accident involving hazardous goods	☐	☐	☐	☐	☐
Fire	☐	☐	☐	☐	☐
Accident at nuclear power plant	☐	☐	☐	☐	☐
Heart attack	☐	☐	☐	☐	☐
Car accident	☐	☐	☐	☐	☐
Struck by lightning	☐	☐	☐	☐	☐

B3. This sub-sample included the item described in B1 above (Q.7. with risk rating from 0 to 10), and an additional item eliciting risk perceptions in everyday life (Q.10.) on a scale 0-10:

Q.10. … In the following, we ask you to evaluate how threatening you perceive the following risks.
Please check the rating that best reflects …

	No risk at all										Very high risk
	0	1	2	3	4	5	6	7	8	9	10
Accident at nuclear power plant	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Appendix C

Table C1

Variable	Self Sufficiency	Unemployment	Greenhouse gases	Nuclear Waste	Competitiveness	Fine Particles	Land for Bioenergy	Energy Saving
Age	-0.003 (0.004)	-0.006* (0.004)	-0.006* (0.004)	-0.003 (0.004)	0.000 (0.004)	-0.008** (0.004)	-0.001 (0.004)	-0.008*** (0.003)
Male	-0.062 (0.110)	0.121 (0.111)	-0.512*** (0.116)	-0.555*** (0.125)	0.044 (0.106)	-0.529*** (0.114)	0.082 (0.112)	-0.116 (0.101)
High Education	0.103 (0.134)	-0.092 (0.135)	-0.052 (0.141)	-0.442*** (0.152)	0.322*** (0.130)	-0.055 (0.138)	-0.015 (0.136)	-0.119 (0.123)
Income	-0.031 (0.026)	-0.023 (0.027)	-0.063** (0.028)	-0.083*** (0.030)	-0.041 (0.025)	-0.073 (0.027)	-0.069 (0.027)	-0.029 (0.024)
Entrepreneur	-0.167 (0.217)	-0.004 (0.221)	-0.185 (0.228)	-0.273 (0.249)	-0.101 (0.215)	-0.114 (0.227)	-0.257 (0.222)	-0.044 (0.200)
Unemployed	0.035 (0.233)	0.458* (0.237)	-0.390 (0.244)	-0.146 (0.271)	0.286 (0.226)	-0.119 (0.243)	-0.281 (0.241)	-0.282 (0.218)
Constituencies	yes	yes	yes	yes	yes	yes	yes	yes
Constant	3.119*** (0.308)	2.762*** (0.311)	3.579*** (0.326)	4.549*** (0.348)	2.684*** (0.299)	3.808*** (0.319)	2.868*** (0.313)	3.464*** (0.282)