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Nuclear Power Plant – a threat to my future or a clean and reliable source of energy

2026

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Introduction

Today, the world faces the need for an energy transition to achieve carbon neutrality. According to the UNECE, nuclear energy is crucial due to having one of the lowest emission levels[7], while the IAEA emphasizes that nuclear safety remains the highest priority in its expansion[1]. Technological progress and research (e.g., within the OECD NEA) continuously improve reactor safety systems, even for extreme conditions [2].

Despite its high level of safety, the industry encounters the barrier of public opinion, marked by historical accidents such as Fukushima[10]. The World Nuclear Association (WNA) states that educating the public and dispelling myths is essential for the acceptance of nuclear energy[5].

The solution to this information gap is the modernization of education, as traditional methods often fail when explaining the abstract processes within a reactor. Research confirms that the active involvement of students[8] and experiential learning according to Kolb's theory[9] significantly increase their understanding. Therefore, in this work, we present an interactive demonstration model of a nuclear power plant. This didactic tool for primary and secondary schools will help students understand complex systems and form an opinion based on technical facts rather than prejudices.

The work is divided into three parts. The first analyzes the theoretical background of nuclear energy and safety. The second, empirical part, examines the respondents' level of awareness before and after interacting with the model. The third, practical part, details the mechanical design, the educational use of the simulator, and the proposed financial budget for its construction.

Theoretical par

1 Current State of the Nuclear Energy Issue in the Era of Decarbonisation

Nuclear energy is currently undergoing a period of so-called "nuclear renaissance" on a global scale. This is driven by the urgent need to decarbonise the energy sector and achieve net-zero carbon neutrality targets by 2050.[1] The main technological trend worldwide is the shift from traditional active safety systems toward passive safety systems, which utilise physical laws such as gravity and natural circulation, and operate without the need for operator intervention or external power supply.[2] Development is focused primarily on small modular reactors (SMRs) and Generation IV reactors, which have the potential to replace ageing coal-fired power plants and increase the stability of energy grids.[4]

In Slovakia, nuclear energy holds a strategic position, providing more than 50% of total electricity production (see Fig. 1). The current state is defined by the successful commissioning of the third unit and the ongoing completion of the fourth unit at Mochovce, placing Slovakia among the leaders in low-emission energy production within the European Union.[3] Despite this technological advancement, the current situation reveals a significant barrier, one that lies not in the technology itself, but in public opinion and a low level of technical literacy. As ongoing surveys show, myths persist in society about "liquid green slime" as a form of nuclear waste, or about the possibility of a reactor exploding like an atomic bomb. perceptions often fuelled by popular culture and insufficient specialist education in schools.[5]

The area of communication and transparency is becoming a key component of addressing nuclear safety issues in 2026. Institutions such as VUJE and the International Atomic Energy Agency (IAEA) emphasise that safety in the modern era does not end at the gates of the power plant, but also encompasses building public trust.[2] A modern approach involves the use of interactive models and simulators of crisis situations, which transform abstract physical concepts into a clear visual narrative. These educational tools are today considered an essential element in overcoming fear of the unknown, as they visibly demonstrate the principle of defence-in-depth and the automatic safety barriers that have long been resolved in modern reactors.[3, 5]

The synthesis of the current state suggests that while global trends are moving toward technological innovation such as SMRs, the local situation in Slovakia requires, alongside the operation of energy sources, intensive investment in energy education. The future of nuclear power therefore depends not only on the laws of physics, but also on the ability of the state and specialists to communicate effectively about the safety and sustainability of this technology for future generations.

2 Theoretical foundation

2.1 Principle of Nuclear Reactor Operation

A nuclear power plant converts the energy released by controlled nuclear fission into electrical energy. When a uranium-235 nucleus is split by neutrons, a large amount of thermal energy is released along with additional neutrons, which initiate further fission reactions, forming a controlled chain reaction. The heat generated in the reactor core heats the coolant of the primary circuit, which transfers its energy in the steam generator to the secondary circuit. The steam produced in the secondary circuit drives a turbine connected to an electrical generator, after which it condenses and returns to the cycle. Pressurized water reactors (PWR, see Fig. 2) currently dominate, in which the primary coolant is kept under pressure to prevent boiling, ensuring stable heat removal from the core.[1]

2.2 Safety of Nuclear Reactors

The safety of modern nuclear reactors is built on the principle of defence-in-depth (see Fig. 3), which consists of multiple independent physical barriers preventing the release of radioactive materials into the environment. These barriers include the fuel matrix, the fuel rod cladding, the reactor pressure vessel, and the hermetic containment structure.[3] A key distinction in modern reactor design is the difference between active and passive safety systems. Active systems require external power and operator intervention to function; passive systems rely exclusively on physical laws, such as gravity and natural convection, and operate even during a complete loss of power supply.[2] Emergency reactor shutdown is carried out via a SCRAM, in which control rods made from materials with high neutron absorption properties such as boron or cadmium are inserted by gravity into the active zone, immediately halting the chain reaction.[4] Historical accidents such as Chernobyl in 1986 and Fukushima Daiichi in 2011 were a direct catalyst for the development of passive safety systems, which physically preclude these scenarios without requiring any human intervention.[10, 11]

2.3 Sustainability of Nuclear Energy

From a sustainability perspective, nuclear energy ranks among the low-emission sources of electrical energy. According to the UNECE report, nuclear energy exhibits one of the lowest lifecycle greenhouse gas emission values of all electricity sources, comparable to wind energy.[7] This property makes nuclear energy a key instrument of energy sector decarbonisation and the achievement of carbon neutrality by 2050, primarily as a stable baseload source capable of compensating for the intermittent output of renewable energy sources. In Slovakia, nuclear energy covers more than 50% of total electrical energy production, placing the country among the leaders in low-emission energy within the European Union.[3]

Empirical part

1 Research

1.1 Methodology and Research Process

The aim of this section is to describe and explain the methods and procedure of the research, which we selected on the basis of data collection from our respondents and their views on nuclear energy before and after being introduced to our educational simulator.

1.2 Research Objective

The primary objective of this empirical research is to analyse the current level of awareness among a selected sample of respondents in the field of nuclear energy. We focus primarily on identifying the most common myths concerning safety and the management of nuclear waste. A secondary objective is to verify the hypothesis of whether interactive visualisation (our model) can represent an effective tool aimed at eliminating public fear regarding the safe use of nuclear energy, compared to commonly available information in textual form.

1.3 Research Hypotheses

Based on theoretical foundations and existing knowledge, we formulated three main research hypotheses:

H1: We assume that respondents perceive nuclear energy as dangerous due to a lack of technological knowledge about the modern safety systems currently in use.

H2: We assume that respondents perceive nuclear waste as a hazardous liquid that can easily leak into the ecosystem.

H3: We assume that the interactive nuclear power plant model will contribute to a better understanding of its processes and a subsequent reduction in fear of nuclear accidents among the target group.

1.4 Research Sample and Data Collection

Data was collected in two ways using a questionnaire. A total of 61 respondents participated in the research, categorised by age, gender, level of education (technical vs.

non-technical background) and the level of knowledge and experience of the respondents surveyed. Data collection was carried out through two channels:

- online - distribution of a digital questionnaire via social media using QR codes
- field survey - respondents completed the questionnaire at the largest shopping centre in Banská Bystrica

1.5 Methodology for Processing Data Before and After Use of the Nuclear Power Plant Simulator Model

The questionnaire is structured to allow comparative analysis. In the first part, we determine the respondents' subjective opinions and knowledge without providing a visual demonstration of our model along with the necessary description to make it sufficiently comprehensible to respondents. In the second part, we provide respondents with an "educational window" describing our power plant model and its internal workings. We then compare the change in their attitudes and opinions before and after interaction with the visual nuclear power plant model.

1.6 Structure of the Research Instrument

The research instrument is a structured questionnaire divided into five logical sections:

1. demographic data and level of education,
2. subjective attitudes and sources of information,
3. a knowledge test focused on common myths,
4. an educational presentation of the model and technical facts,
5. evaluation of attitude change and the impact of visual simulation on respondents.

2 Evaluation of Research in the Field of Nuclear Energy

2.1 Demographic Composition of Respondents and Level of Knowledge

A total of 61 respondents participated in the research. In terms of gender, the sample consisted of 25 women (41%) and 36 men (59%). (see Fig. 11)

The largest group consisted of young people aged 15–25 (65.6%), followed by the 26–45 age category (31.1%), with the remainder being respondents aged 46–65 (3.3%). The over-65 category was not represented. (see Fig. 9)

In terms of education and field of study, the following groups participated:

- primary education / primary school pupils: 13.1% (8 respondents)
- secondary education - technical: 14.8% (9 respondents)
- secondary education - other: 44.3% (27 respondents)
- higher education - technical: 3.3% (2 respondents)
- higher education - other (humanities, medical, and other): 24.6% (15 respondents) (see Fig. 12)

2.2 Distance from a Nuclear Power Plant

More than half of respondents (**54.1%**) live more than 50 km away. A notable finding is that as many as **31.1%** of respondents do not know how far they live from the nearest nuclear facility. The option "other" was not selected by any respondent. (see Fig. 13)

2.3 Assessment of Respondents' Knowledge in the Field of Nuclear Energy

The largest group of respondents (31.1%) reported having an intermediate level of knowledge in the field of nuclear energy (level 3), while 31.2% of those surveyed perceive their knowledge as rather low (27.9% chose level 2 and 3.3% chose the lowest level 1), and the remaining 37.7% of respondents leaned toward an above-average to excellent self-assessment of their knowledge (26.2% for level 4 and 11.5% for the highest level 5).

2.4 Sources Influencing Respondents' Opinions

The greatest influence on respondents' opinions comes from **news in the media and on the internet (70.5%)**. As many as 41% of respondents stated that their views on nuclear energy safety were influenced by documentary films. 34.4% of those surveyed indicated that they acquired most of their knowledge at school. The option of films and popular culture was chosen by 24.6% of respondents. The "other" option was not selected by any respondent. (see Fig. 14)

2.5 Respondents' Perception of the Safety of a Modern Power Plant

When rating safety on a scale from 1 (safest) to 10 (least safe), the majority of respondents leaned toward a positive perception. Maximum confidence was expressed by **8.2%** of those surveyed (level 1). The dominant values were 2 and 4, each selected by **21.3%** of respondents, while level 3 was chosen by **13.1%** and the middle value of 5 by **14.8%** of participants. Toward the negative end, perception gradually declined: level 6 was selected by **4.9%**, level 7 by **11.5%**, and the more critical values of 8, 9, and 10 were each indicated by **1.6%** of respondents. (see Fig. 15)

2.6 Respondents' Greatest Concerns Regarding the Use of Nuclear Energy

Respondents (with the option to select multiple answers) expressed the greatest concerns about **nuclear accidents (50.8%)**, **the danger of waste (44.3%)** and **military misuse (39.3%)**. They were further concerned about human factor failure (37.7%), environmental impact (24.6%) and long-term waste storage (23%). Only 8.2% of those surveyed have no concerns. The open-ended "other" option was not used by any respondent. (see Fig. 16)

2.7 Knowledge Test — Myths versus Reality

2.7.1 The Origin of the "White Smoke" from Cooling Towers

As many as **49.2%** of respondents selected the correct answer, that the white vapour originates from water steam. A concerning finding is that **27.9%** of those surveyed believe it consists of greenhouse gases, and **11.5%** consider it to be radioactive vapour. The option "other" *(the cloud fairy is shaking out her duvets)* was chosen by 1 respondent (1.6%). 9.8% of respondents were unable to answer. (see Fig. 17)

2.7.2 The Possibility of a Reactor Exploding Like an Atomic Bomb

The majority (**60.7%**) of respondents correctly stated that it is not possible for a reactor to explode like an atomic bomb. Almost a quarter (**24.6%**) were unable to answer this question, and **14.8%** believe this popular myth. (see Fig. 18)

2.7.3 Causes of Reactor Failures in the Past

Respondents correctly identified **operator/human error (70.5%)** as the main cause of reactor failures in the past. Technology failure was selected by 41% of those surveyed, and natural disaster by 37.7%. The answer "I don't know" was chosen by 11.5% of respondents. (see Fig. 19)

2.7.4 The Form of the Most Dangerous Nuclear Waste

Only exactly half of the research participants (**50%**) know that the most dangerous form of nuclear waste consists of **solid metal rods**. The remainder lean toward gas (23.3%) or do not know (25%). The myth of "liquid green slime" persists among 8.3% of respondents. (see Fig. 20)

2.8 Assessment of the Contribution of the Nuclear Power Plant Model as a Didactic Aid in Education

2.8.1 Change in Respondents' Attitudes After Being Introduced to the Model

As many as **70.5%** of respondents believe that had they had access to the model and its description before completing the questionnaire, their previous answers would have changed. This confirms the high effectiveness of visual demonstration aids. Only 8.2% of respondents believe they would not have changed their answers. 6.6% indicated the option "I don't know". (see Fig. 21)

2.8.2 Use of Interactive Models in Schools

The overwhelming majority, **93.5%** of those surveyed (52.5% yes, 41% rather yes), believe that such models should be used in schools. The option "no" was not selected by anyone. The options "rather no" and "I don't know" were chosen by an equal number of respondents at 3.3% each. (see Fig. 22)

2.8.3 Increase in the Sense of Safety Regarding the Use of Nuclear Energy in Connection with the Integration of the Simulator into the Educational Process

If respondents were able to try the simulator in practice, their sense of safety would increase for **88.3%** of them (45% yes, 43.3% rather yes). The option "rather no" was chosen by 5% and "I don't know" by 6.7%. (see Fig. 23)

3 Generalisation of Results and Recommendations for Educational Activity

The aim of the work was to determine whether the nuclear power plant simulator model has an impact on respondents' perception of the safety of nuclear energy use.

The findings indicate the following:

- **H1** - ***was confirmed.*** Respondents with a non-technical educational background (approximately 82% of the sample in total) showed a higher susceptibility to myths (e.g. 11.5% believe in radioactive smoke) compared to respondents with a technical background.
- **H2 - was confirmed.** Half of the respondents (50%) correctly identified the solid form of spent fuel. However, as many as 31.6% are subject to visual myths and perceive waste in an incorrect state of matter – as a gas (23.3%) or as a hazardous liquid (8.3%).
- **H3** - ***was confirmed.*** **93.5%** of respondents believe that the use of visual demonstration and interactive models in the educational process could increase awareness among primary and secondary school pupils and students regarding the safe use of nuclear energy.

Based on the findings, we propose the following recommendations for teaching nuclear energy safety:

1. **Implementation of our visual demonstration, interactive model into teaching -** the data shows that direct contact of research participants with the nuclear power plant simulator model eliminates fear in almost 90% of respondents. Our model physically demonstrates safety barriers, thereby refuting myths about explosion (question no. 10).
2. **A targeted "Steam, not smoke" campaign -** since half of respondents do not know what comes out of the towers, we propose educational panels placed near power plants and in schools that visually explain the water cycle.
3. **Digitalisation in the form of smartphone simulators -** as many as 65.6% of respondents are young people, so it is necessary for education to be delivered through digital and gamified formats, enabling it to compete with the influence of online news (the primary source for 70.5% of those surveyed).

4.

Practical part

1 Nuclear power plant simulator

The practical part of our project represents the design and construction of an interactive nuclear facility model intended as an educational simulator. This chapter will go over the details of the concept of this model-simulator, its proposed mechanical design, control system, etc. The presented model serves as a proposal that could in the future be used as a teaching aid for students at secondary technical schools and vocational schools specializing in electrical engineering with a focus on energy systems.

1.1 Concept and Design philosophy

The interactive nuclear reactor model presented in this project was designed based on our hypotheses, namely our first hypotheses that respondents perceive nuclear energy as dangerous as a result of a lack of technical knowledge about the functioning and safety of modern nuclear reactors. If the core of the problem lies in insufficient technical knowledge, the only solution we see is the education of future primary and secondary school students within physics classes or specialized subjects related to energy studies.

The dominant method of science education in secondary schools remains lecture-based instruction supplemented by static diagrams and textbook descriptions. While adequate for conveying factual information, this approach has well-documented limitations when applied to complex dynamic systems, particularly those involving invisible physical phenomena such as neutron flux, thermal hydraulics, or automated control logic. A student who has read a description of a SCRAM sequence has acquired information; a student who has triggered one and watched the control rods drop while alarms activate has built intuition. Research in educational psychology consistently supports the superiority of active, multisensory learning over passive reception for both knowledge retention and attitude change toward unfamiliar subjects.[8]

Our model-simulator is designed to exploit this advantage directly. The model provides real-time visual feedback through LED indicators, analogue-style meters, and status displays, giving students an immediate and legible representation of reactor state. Physical controls, such as the control rod mechanism and the emergency scenario triggers, allow students to interact with the system rather than observe it passively. This is particularly significant for the emergency scenarios: when a student personally triggers a coolant pump failure and watches the automatic SCRAM execute without any intervention on their part, the abstract concept of passive safety becomes concrete and memorable in a way that no diagram can replicate.

The simulator is also designed with the specific demographics of our target audience in mind. Our survey results confirm what our hypotheses anticipated: respondents with a low level understanding of nuclear energy consistently rated it as more dangerous, while those same respondents predominantly cited informal media as their sources of exposure to the topic, including news coverage of historical accidents and cultural representations in film and television (see Figure 14). Formal education ranked lower as an information source, confirming that public perception of nuclear energy is formed largely outside any scientifically grounded context.

The design philosophy of the simulator rests on three principles. First, physical fidelity where feasible: the model reproduces the structural layout, operational logic, and safety response behaviour of a real pressurized water reactor as closely as the scale and materials permit. Second, honest abstraction: phenomena that cannot be safely or practically reproduced, i.e. heat generated by fission, actual neutron flux, radioactive materials, are replaced by clearly labelled electrical analogs, ensuring the model is educationally transparent rather than misleading. Third, the simulator itself is designed such that any hardware fault, power loss, or unexpected condition results in control rods inserting and all systems returning to a safe idle state, mirroring the safety philosophy it is designed to teach.

Regarding deployment, the project currently envisions two operational paths depending on available funding. In the primary scenario, a single model is constructed and transported to schools by the authors, who conduct structured interactive sessions with student groups directly. In the event of expanded funding, multiple units would be produced and distributed to partner schools, accompanied by a training programme equipping teachers with the knowledge and methodology needed to use the simulator independently as part of their curriculum. Both paths are designed to be scalable, so that the model becomes part of interactive teaching within science or specialist subjects.

1.2 Mechanical design

The physical structure of the simulator represents a complete nuclear power facility at reduced scale, rather than an isolated reactor vessel. The model encompasses the key functional sections of a real plant, such as the reactor vessel, the steam generator, the turbines, and the cooling system, arranged in a spatial layout that reflects their actual relationships within a facility. This breadth is prioritised over fine mechanical detail. Where a full-scale PWR may contain hundreds of fuel assemblies and dozens of control rod clusters, the simulator condenses these into a smaller number of representative components sufficient to convey the operational logic without overwhelming the observer. The goal is for a student to look at the model and immediately understand the flow of energy from the reactor core to the electrical output, and the flow of safety logic from sensors back to the control rods.

The reactor vessel is the centerpiece of the model, constructed as a full cylinder with a quarter section removed to expose the interior. This cutaway approach gives students a direct view of the core internals, i.e. the fuel assemblies, control rods, and coolant flow paths, without requiring any disassembly, making it ideal for live demonstrations. The vessel houses two to three removable fuel assemblies represented by cylindrical rods at an appropriate scale, whose removability makes the concept of refuelling tangible. The control rods are mounted on a vertical drive mechanism actuated by a servo motor controlled by the Arduino. Under any SCRAM condition, the servo is de-energised and the rods fall to the fully inserted position under gravity, with no active signal required. In addition to the functional components, individual sections of the model are equipped with dedicated illumination, activated by buttons on the operator panel. This allows a presenter to highlight specific parts of the facility, such as the reactor core, steam generator, or the turbines, during an explanation, directing student attention to the relevant section of the model in real time.

The primary and secondary coolant circuits are represented by half-section pipe segments routed through the model between the reactor building, the steam generator, and the turbines. Rather than circulating actual water, coolant flow is simulated by LED strips mounted inside the pipe segments, with light sequenced in the direction of flow to give a clear visual impression of circulation. This approach sacrifices hydraulic realism in favour of reliability, cost, and ease of demonstration. Students can follow the entire flow path at a glance without the risk of leaks or pump maintenance. Flow rate changes, loss-of-flow events, and the distinction between the primary and secondary circuits are all communicated through changes in LED behaviour, such as speed, colour, or cessation of the animation sequence.

The overall scale and construction of the model are also governed by its intended use case. Figure 24 presents an indicative 3D render of the simulator, illustrating the proposed spatial arrangement of the individual components and the overall appearance of the model. The simulator is designed to be disassembled and transported between schools for interactive sessions, so all structural sections are modular, connect without tools, and fit within a footprint suitable for a standard classroom demonstration table.

1.3 Sensors and Measurement systems

Accurate real-time monitoring is central to the educational value of the simulator. A key goal of this section of the design is to reflect the instrumentation philosophy of a real nuclear facility. The state of the reactor is continuously measured, that all critical parameters have defined safe operating ranges, and that any deviation from those ranges triggers an automatic protective response. The parameters monitored by the simulator are simulated core temperature and reactor pressure, coolant flow rate, control rod position, simulated thermal power level, and simulated generated electrical output in megawatts.

Core temperature and pressure are not measured directly due to the simulator operating at room temperatures and atmospheric pressures. They are instead computed based on coolant flow rate and control rod position. Both values feed into the alarm logic and are used to determine whether operating conditions remain within a defined safe envelope. Coolant flow rate is inferred from the LED animation state of the primary circuit: when the flow animation is running at its nominal speed, flow is considered normal, whereas any reduction or cessation is interpreted as a loss-of-flow condition. Control rod position is tracked continuously via a potentiometer coupled to the servo drive shaft, giving the Arduino a precise analogue value for rod insertion depth at all times. Thermal power level is expressed as a percentage of nominal output, while generated electricity is expressed in simulated megawatts and updated in real time.

This data is presented to the operator and students through three complementary display layers. The primary layer consists of physical analogue needle gauges mounted on the control panel, displaying core temperature, reactor pressure, and power level. We chose these analogue gauges due to their immediate readability of their respective measured parameter. They can also be found in real reactor control panels, reinforcing the connection between the model and an actual facility. The secondary layer is a seven-segment display showing the simulated generated electrical output in megawatts, giving students a concrete and continuously updating number to associate with the reactor's operating state. The tertiary layer consists of individual LED status indicators for each major system and condition: coolant circuit status, control rod position status, reactor pressure, and a dedicated SCRAM indicator that illuminates whenever an emergency shutdown has been triggered. These indicators give an at-a-glance summary of facility health and make fault conditions immediately visible even from across a classroom.

1.4 Control system and User Interface

The control system of the simulator is built around an Arduino microcontroller, which serves as the central processing unit responsible for reading all sensor inputs, computing derived parameters, updating display outputs, enforcing alarm thresholds, and executing automatic protective responses. The Arduino was selected for this role due to its low cost, wide availability, sufficient input/output capacity for the required signal count, and the ease with which its behaviour can be modified.

The operator interface is a custom-built control panel constructed by the authors. All interactive elements such as buttons, switches, needle gauges, the seven-segment display, and LED status indicators are mounted on a single panel designed to resemble the instrumentation layout of a real reactor control room in a simplified form. The panel is the sole point of interaction between the operator and the simulator. All commands pass through it and all system status information is returned to it, creating a clean and self-contained interface that students can approach without prior technical knowledge.

The intended operational model for a classroom session follows a structured two-phase approach. In the first phase, the teacher or lecturer operates the panel while guiding students through the normal operating state of the reactor, explaining each gauge, indicator, and control in turn, with the model's illuminated sections used to direct attention to the relevant physical component being discussed. This phase establishes a baseline understanding of normal reactor behaviour before any fault conditions are introduced. In the second phase, students are invited to interact with the panel directly, including triggering the emergency scenarios described in section 1.5. This transition from passive observation to active participation is deliberate: research in experiential learning consistently shows that students retain information more effectively when they are the ones initiating the event they are observing[9], rather than watching someone else do so. Based on working with the model, pupils/students will understand how the reactor responds in individual situations

1.5 Emergency scenarios simulation

The central feature of the model-simulator is its ability to reproduce and resolve emergency conditions in a controlled and repeatable manner. Each scenario is triggered by a dedicated button or system on the operator panel. Rather than introducing actual faults into the hardware, which would compromise safety and repeatability, the Arduino-based control system interprets a button press as a fault injection signal and executes a pre-programmed response sequence that faithfully mirrors how a real reactor would behave under those conditions. This approach allows students to observe both the onset of an abnormal event and the subsequent automatic protective response without any risk. All scenarios culminate in a SCRAM, an emergency shutdown (see Fig. 25) in which the reactor control rods are driven fully into the reactor core, terminating the simulated fission reaction.

1.5.1 Operator error

In a real pressurized water reactor, control rods regulate the neutron flux within the reactor core by absorbing excess neutrons, which regulates the reaction strength by proxy. If an operator withdraws the control rods at an excessively high rate, the neutron population grows faster than the reactors automatic control systems compensate for. This causes a rapid and uncontrolled power excursion. This type of operator error was a contributing factor in the Chernobyl disaster of 1986[11], making it a historically significant scenario for educational purposes.

In our simulator, this scenario can be triggered by excessively fast withdrawal of the control rods by the control rod control mechanism. Triggering this scenario causes the simulated reactor power level and generated electrical output to rise sharply into the warning range, sounding audio-visual alarms. The Arduino detects the rate of change exceeding a defined threshold and, after a brief delay representing the reactor's response time, executes a full SCRAM: all control rods return to the fully inserted position and the power indicators drop back to idle.

The students directly observe the consequence of the erroneous action, reinforcing the principle that modern reactor control systems enforce hard safety limits automatically and quickly, independent of operator judgement.

1.5.2 Stuck control rods

Mechanical failure of control rod drive mechanisms represents one of the most safety-critical hardware faults in a nuclear facility. If control rods cannot be inserted into the core on demand, the primary means of rapid power reduction is lost. Real reactor designs address this through redundancy. Multiple independent rod clusters ensure that the failure of any single drive mechanism does not prevent shutdown. Another popular option to address this situation is through passive insertion, where rods fall into the core under gravity if power to the drives is lost.

When this scenario is triggered, the Arduino locks the control rod servo in its current position and activates a fault indicator, an LED, on the panel, signalling a drive mechanism failure. The system then demonstrates the passive safety response: power to the rod drive mechanism is cut, and the control rods drop to the fully inserted position under simulated gravity, therefore physically showing the student that the fail-safe state of the system is always shutdown. The alarm clears once full insertion is confirmed by the position sensor, illustrating that passive safety does not require any corrective action from the operator.

1.5.3 Coolant pump failure

The primary coolant circuit is responsible for removing heat from the reactor core. Loss of coolant flow, that may be caused by pump failure, pipe rupture, or loss of electrical supply to the pumps, leads to a rapid rise in core temperature, signalled by the reactor core thermal indicator LEDs changing to a bright red colour. If uncorrected, this results in fuel damage and, in severe cases, core meltdown. Modern reactor designs mitigate this through passive cooling systems that rely on natural convection rather than active pumping, requiring no power or operator intervention.

In the simulator, triggering this scenario stops the animation of the cooling circuit and begins increasing the simulated core temperature through the LED thermal indicators.. As the temperature crosses the first alarm threshold, a warning indicator activates. If the temperature continues to rise and reaches the SCRAM threshold, which occurs within a configurable time window, the Arduino automatically triggers a full shutdown: control rods insert, the pump restart sequence is initiated, and the temperature indicators begin returning to normal. The scenario clearly demonstrates that the reactor does not require human intervention to prevent escalation; the protection system responds autonomously based on measured parameters.

1.5.4 Electrical blackout

A station blackout, the complete loss of external electrical power, is one of the most demanding scenarios a nuclear facility can face, as it simultaneously affects active cooling, instrumentation, and control rod drive mechanisms. It was the initiating event of the Fukushima Daiichi accident in 2011[10]. Modern reactor designs address this through passive safety systems that function without any electrical supply, most critically through gravity-driven control rod insertion.

When this scenario is triggered, the simulator cuts power to all active systems simultaneously: the coolant pump stops, active displays go dark, and the control rod drives are de-energised. The control rods then drop to the fully inserted position purely under gravity, with no signal required from the Arduino. This is the most visually impactful demonstration in the simulator, as the students see all active systems fail at once while the single most important safety action, the SCRAM reactor shutdown, occurs automatically and instantaneously without any power source. After the blackout state is established, a backup indicator illuminates to confirm that the core is in a safe, shut-down state.

1.5.5 Summary

The four scenarios described above collectively demonstrate the core safety philosophy of modern nuclear reactor design: that the safe state of a reactor is always shutdown, that this state is reached automatically without human intervention, and that multiple independent mechanisms exist to guarantee it even under compounding failures. By interacting with each scenario directly, students gain an intuitive understanding of concepts such as passive safety, redundancy, defence-in-depth, which are difficult to convey through purely descriptive means.

2 Use of the Model as a Didactic Aid in the Teaching Process

The main contribution of the proposed model is the transformation of abstract theory into a tangible experience. The results of our research confirmed that as many as 93.5% of respondents consider interactive models to be an essential part of modern teaching. (see Fig. 22.) We believe that in a school environment, the model can be of significant benefit for understanding and explaining the topic of nuclear energy within the subject of physics or specialist subjects at secondary schools, enabling students to:

- visualise defence-in-depth — the model physically demonstrates safety barriers, directly addressing the fear of nuclear accidents reported by as many as 50.8% of those surveyed
- simulate process control — interaction with the simulator increases the sense of safety and control in 88.3% of respondents; the pupil/student ceases to be a passive recipient of facts and becomes an active participant in the process
- dismantle entrenched myths — 49.2% of research participants know that water vapour comes out of the cooling towers; the model serves as a key tool for explaining the separation of the radioactive and cooling circuits

The model also has an environmental contribution, consisting primarily in its ability to objectively present nuclear energy as a low-carbon source. Research showed that as many as 70.5% of respondents reconsidered their knowledge after viewing a visual demonstration of the model. The model teaches that nuclear energy is a stable zero-emission pillar, which is key to understanding the fight against climate change

3 Contribution of the Model to Social Practice

The research results clearly show that fear of nuclear energy among respondents (waste 44.3%, accidents 50.8%) stems from insufficient understanding due to a low level of acquired knowledge, without visual demonstration didactic aids whose role is to actively engage the pupil/student in the learning process when acquiring subject matter in the field of nuclear energy. We also see the real contribution of this model in the fact that by understanding the safe use of nuclear energy, we can eliminate public prejudice against the threats arising from the use of nuclear energy.

A school equipped with this model is capable of preparing a generation that will approach energy issues rationally rather than emotionally. The model is designed to be usable not only in physics lessons, but also within environmental education or public outreach lectures.

4 Financial Budget

This chapter presents the estimated financial budget of the project, which we propose with regard to the use of the model either as a single didactic aid or for the serial production of these models and their distribution to selected types of primary and secondary schools. All stated amounts are indicative estimates based on current market prices of components and services available on the Slovak market.

4.1 Single Model, Mobile Presentation

We will construct a single simulator model, which we will subsequently transport with us for the purpose of presenting nuclear energy and its safe use at individual schools.

The total estimated budget in this case would range between 255 € and 420 € (see Tables 1 and 2). This option can represent the pilot phase of the project, enabling verification of the simulator's educational impact on pupils/students and its application in broader use.

4.2 Serial Production of the Model and its Long-Term Distribution

This option involves the serial production of models, where models are manufactured on an ongoing basis and distributed to schools according to available funding. Rather than a fixed number of units, this option focuses on repeated production, which reduces the unit cost thanks to bulk purchasing of components and an established production process. As an indicative example, the range of 3 to 5 model units constructed in the first phase could serve as a springboard for the production of further models in subsequent years.

We would like to distribute these first models to partner schools so that they become an integral part of the teaching process in the field of nuclear energy. For the production of 3 to 5 model units, we estimate the cost per unit in the range of 160 € to 265 € (see Table 3). This option also includes one-time costs, which we expect to fall in the range of 235 € to 385 € (see Table 4).

The total estimated budget for this second option depends on the number of model units produced and ranges from 715 € to 1,710 €, including all one-time expenses. The lower bound corresponds to the production of 3 units at the lowest estimated costs, and the upper bound to the production of 5 units at the highest estimated costs.

4.3 Comparison

The first option represents a low-cost entry point achievable with minimal funding, which enables the immediate realisation of the project and allows us to determine within a relatively short time whether our model is an effective didactic aid in the teaching process. The second option is the long-term vision of this project. With each unit produced and distributed, the number of schools with permanent access to the simulator grows, and therefore so does the number of pupils/students the project can reach each year. Both options are designed to be scalable — production volume can be adjusted at any time to match available funding without requiring any fundamental change to the construction or logistics of the project.

Conclusion

In this work, we addressed nuclear energy as a key pillar of decarbonisation and stable global energy systems. Our aim was not only to evaluate technological progress in the field of passive safety and small modular reactors (SMRs), but above all to connect these technical facts with the real perception of the public.

Our empirical research confirmed that public acceptance of nuclear energy is still limited by persistent myths — for example, nearly a third of respondents still hold an incorrect idea about the form of nuclear waste. We found that the key to changing this situation is the use of modern educational technologies.

The main practical contribution of this work is therefore the design and construction of our own interactive model — a nuclear power plant simulator controlled by an Arduino microcontroller. This didactic tool demonstrates complex processes including emergency scenarios and directly refutes lay concerns. The results of our research clearly confirmed its effectiveness: for nearly 88% of respondents, interaction with such a simulator would directly increase their sense of safety.

Nuclear energy has all the prerequisites to play a central role in the clean energy mix of the future. We believe that our functional model and findings will lead to a better understanding of the technical facts and context surrounding the use and safety of nuclear energy in schools, and will help eliminate unfounded prejudices. This didactic tool, among others, can contribute to an open dialogue about the safe and ecological future of nuclear energy among the general public.

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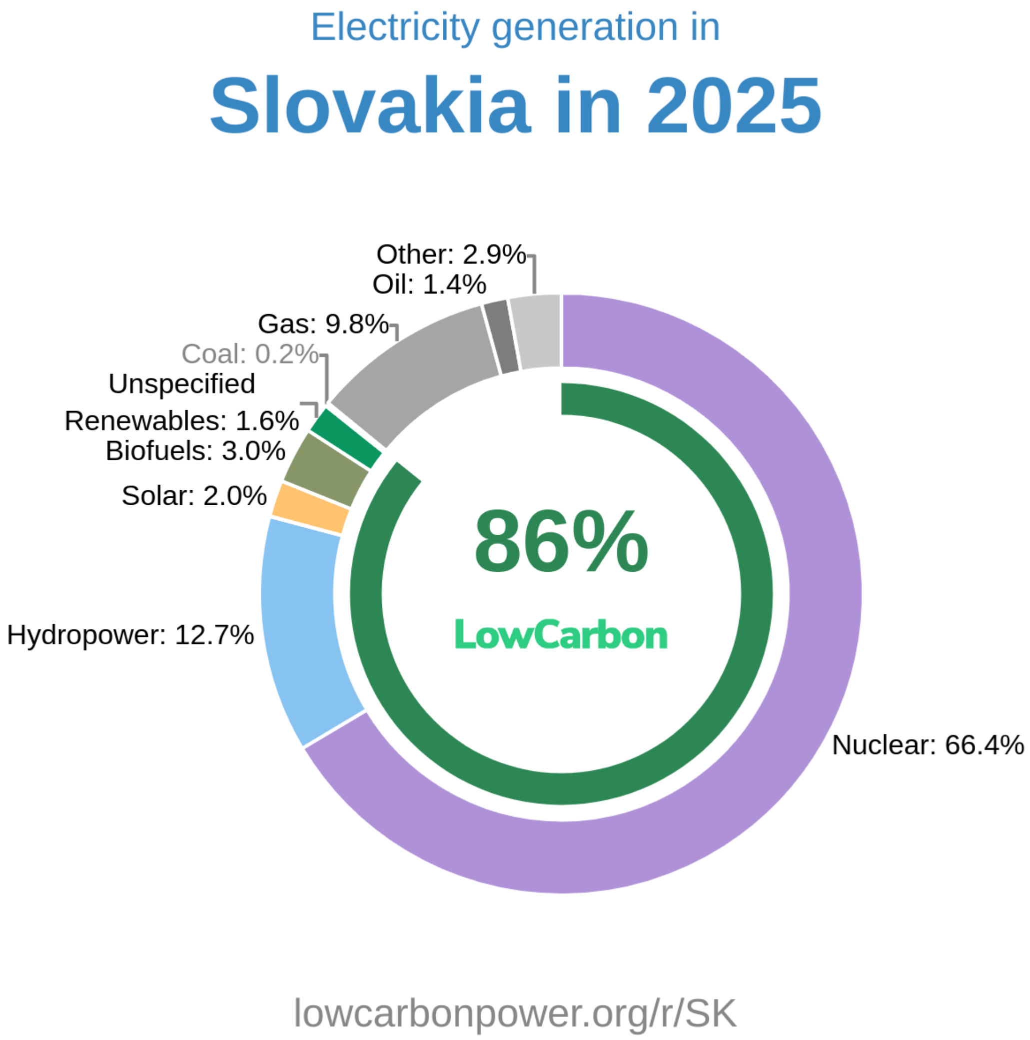
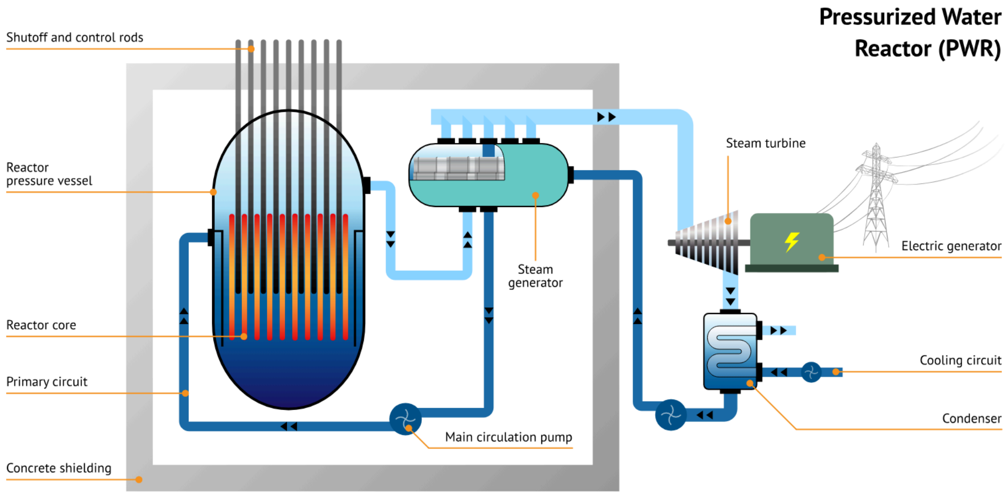
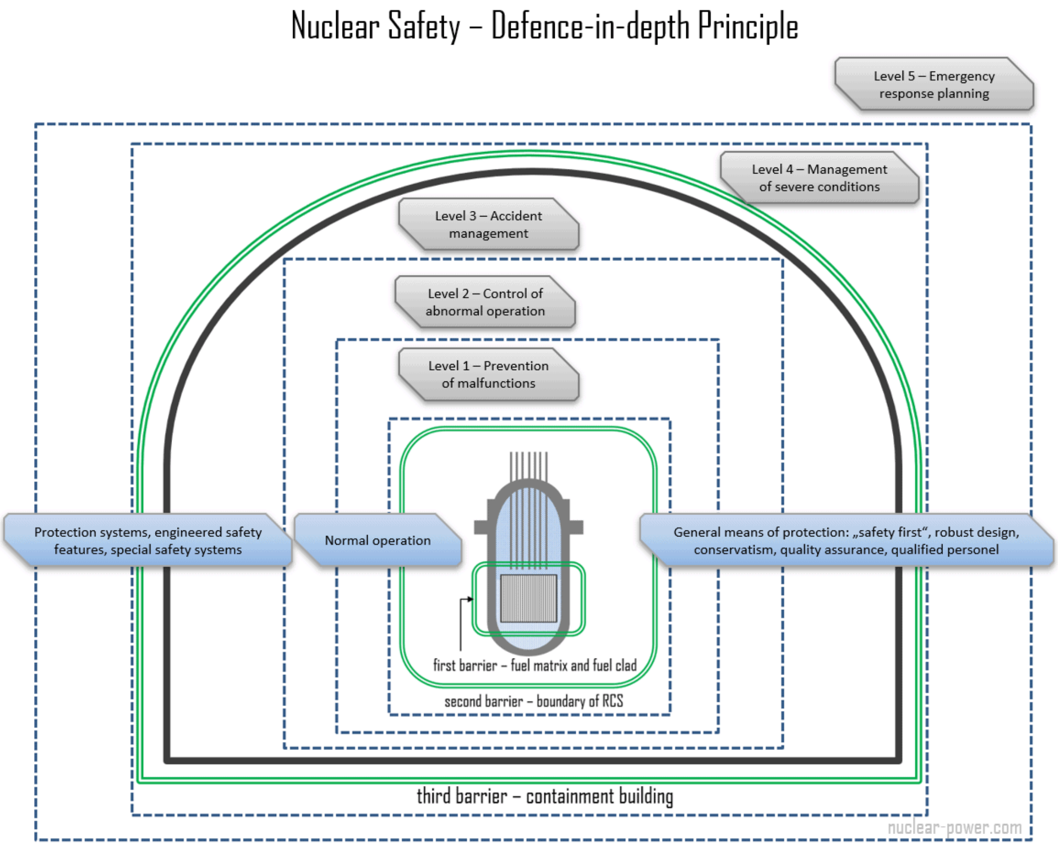
Appendices


Electricity generation in
Slovakia in 2025
Other: 2.9%
Oil: 1.4%
Gas: 9.8%
Coal: 0.2%
Unspecified
Renewables: 1.6%
Biofuels: 3.0%
Solar: 2.0%
Hydropower: 12.7%
86%
LowCarbon
Nuclear: 66.4%
lowcarbonpower.org/r/SK

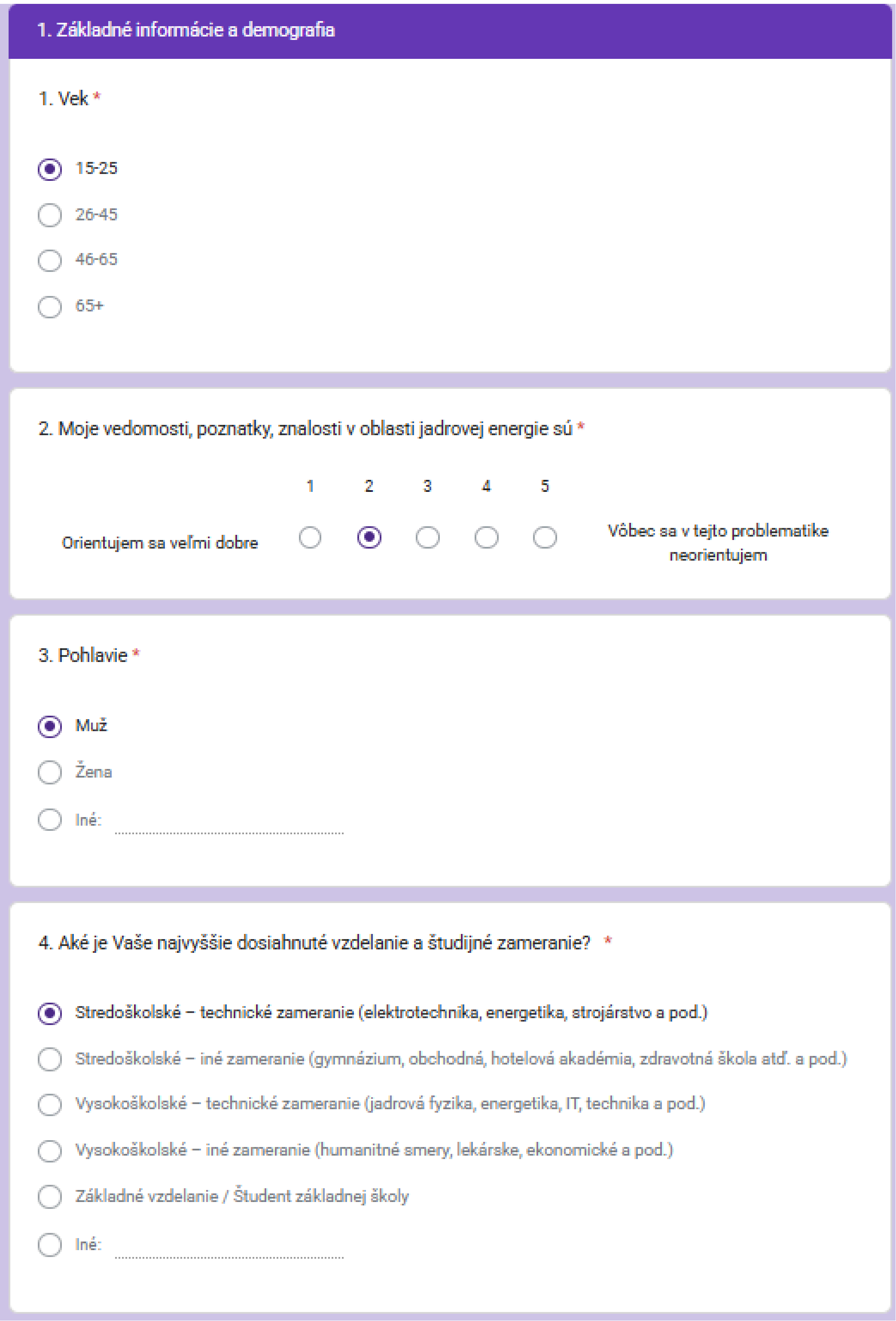
(Fig. 1)


Pressurized Water
Reactor (PWR)
Shutoff and control rods
Reactor
pressure vessel
Reactor core
Primary circuit
Concrete shielding
Steam
generator
Main circulation pump
Steam turbine
Electric generator
Cooling circuit
Condenser

(Fig. 2)


Nuclear Safety – Defence-in-depth Principle
Level 5 – Emergency response planning
Level 4 – Management of severe conditions
Level 3 – Accident management
Level 2 – Control of abnormal operation
Level 1 – Prevention of malfunctions
Protection systems, engineered safety features, special safety systems
Normal operation
General means of protection: „safety first“, robust design, conservatism, quality assurance, qualified personel
first barrier – fuel matrix and fuel clad
second barrier – boundary of RCS
third barrier – containment building
nuclear-power.com

(Fig. 3)



1. Základné informácie a demografia

1. Vek *

● 15-25
○ 26-45
○ 46-65
○ 65+

2. Moje vedomosti, poznatky, znalosti v oblasti jadrovej energie sú *

	1	2	3	4	5	
Orientujem sa veľmi dobre	○	●	○	○	○	Vôbec sa v tejto problematike neorientujem

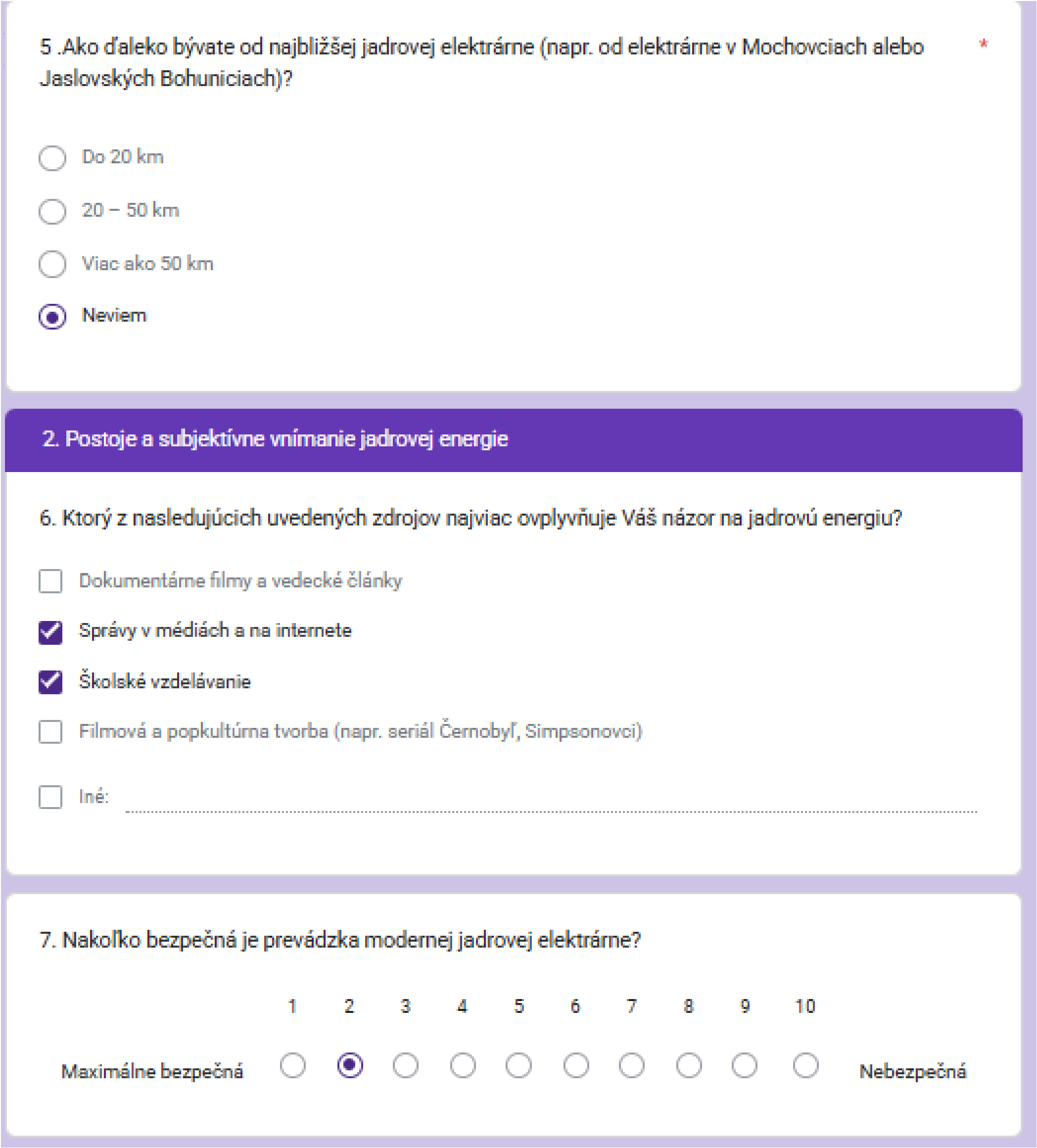
3. Pohlavie *

● Muž
○ Žena
○ Iné: ....

4. Aké je Vaše najvyššie dosiahnuté vzdelanie a študijné zameranie? *

● Stredoškolské – technické zameranie (elektrotechnika, energetika, strojárstvo a pod.)
○ Stredoškolské – iné zameranie (gymnázium, obchodná, hotelová akadémia, zdravotná škola atď. a pod.)
○ Vysokoškolské – technické zameranie (jadrová fyzika, energetika, IT, technika a pod.)
○ Vysokoškolské – iné zameranie (humanitné smery, lekárske, ekonomické a pod.)
○ Základné vzdelanie / Študent základnej školy
○ Iné: ....

(Fig. 4)



5 .Ako ďaleko bývate od najbližšej jadrovej elektrárne (napr. od elektrárne v Mochovciach alebo Jaslovských Bohuniciach)? *

○ Do 20 km
○ 20 – 50 km
○ Viac ako 50 km
● Neviem

2. Postoje a subjektívne vnímanie jadrovej energie

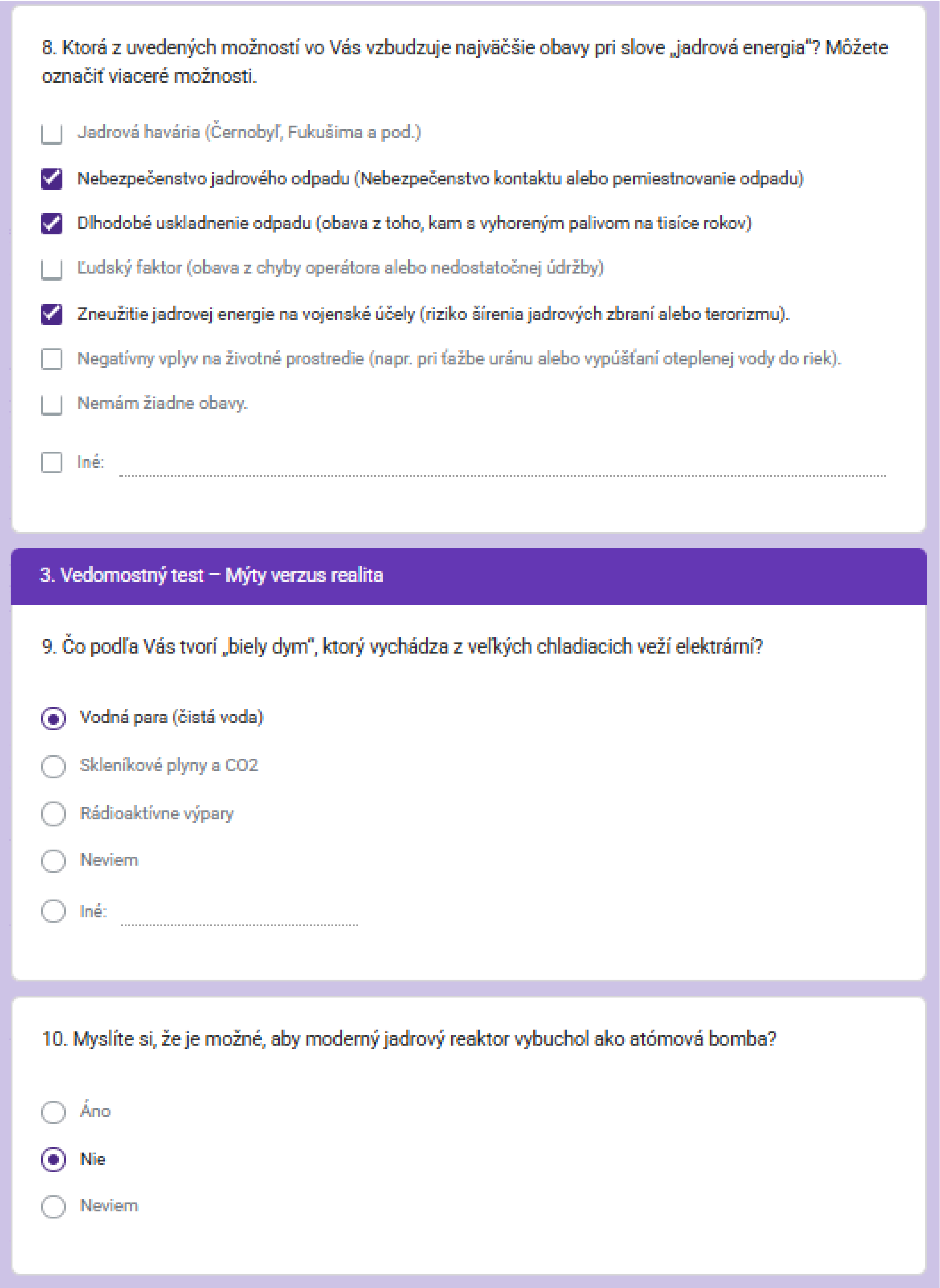
6. Ktorý z nasledujúcich uvedených zdrojov najviac ovplyvňuje Váš názor na jadrovú energiu?

☐ Dokumentárne filmy a vedecké články
☑ Správy v médiách a na internete
☑ Školské vzdelávanie
☐ Filmová a popkultúrna tvorba (napr. seriál Černobyľ, Simpsonovci)
☐ Iné: ____________

7. Nakoľko bezpečná je prevádzka modernej jadrovej elektrárne?

	1	2	3	4	5	6	7	8	9	10	
Maximálne bezpečná	○	●	○	○	○	○	○	○	○	○	Nebezpečná

(Fig. 5)



8. Ktorá z uvedených možností vo Vás vzbudzuje najväčšie obavy pri slove „jadrová energia"? Môžete označiť viaceré možnosti.

☐ Jadrová havária (Černobyľ, Fukušima a pod.)
☑ Nebezpečenstvo jadrového odpadu (Nebezpečenstvo kontaktu alebo pemiestnovanie odpadu)
☑ Dlhodobé uskladnenie odpadu (obava z toho, kam s vyhoreným palivom na tisíce rokov)
☐ Ľudský faktor (obava z chyby operátora alebo nedostatočnej údržby)
☑ Zneužitie jadrovej energie na vojenské účely (riziko šírenia jadrových zbraní alebo terorizmu).
☐ Negatívny vplyv na životné prostredie (napr. pri ťažbe uránu alebo vypúšťaní oteplenej vody do riek).
☐ Nemám žiadne obavy.
☐ Iné: ....

3. Vedomostný test – Mýty verzus realita

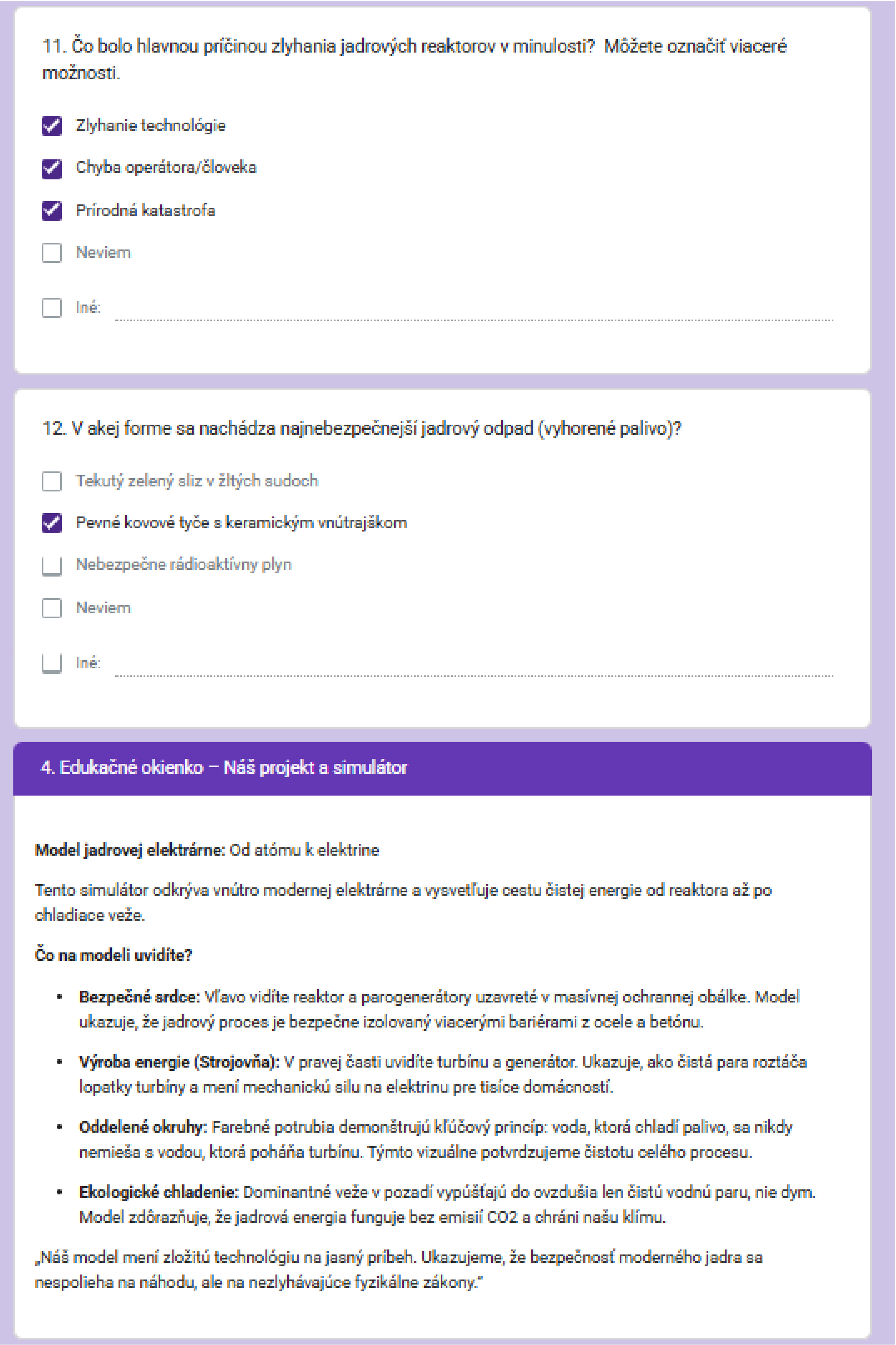
9. Čo podľa Vás tvorí „biely dym", ktorý vychádza z veľkých chladiacich veží elektrární?

● Vodná para (čistá voda)
○ Skleníkové plyny a CO2
○ Rádioaktívne výpary
○ Neviem
○ Iné: ....

10. Myslíte si, že je možné, aby moderný jadrový reaktor vybuchol ako atómová bomba?

○ Áno
● Nie
○ Neviem

(Fig. 6)



11. Čo bolo hlavnou príčinou zlyhania jadrových reaktorov v minulosti? Môžete označiť viaceré možnosti.

☑ Zlyhanie technológie

☑ Chyba operátora/človeka

☑ Prírodná katastrofa

☐ Neviem

☐ Iné: ……

12. V akej forme sa nachádza najnebezpečnejší jadrový odpad (vyhorené palivo)?

☐ Tekutý zelený sliz v žltých sudoch

☑ Pevné kovové tyče s keramickým vnútrajškom

☐ Nebezpečne rádioaktívny plyn

☐ Neviem

☐ Iné: ……

4. Edukačné okienko – Náš projekt a simulátor

Model jadrovej elektrárne: Od atómu k elektrine

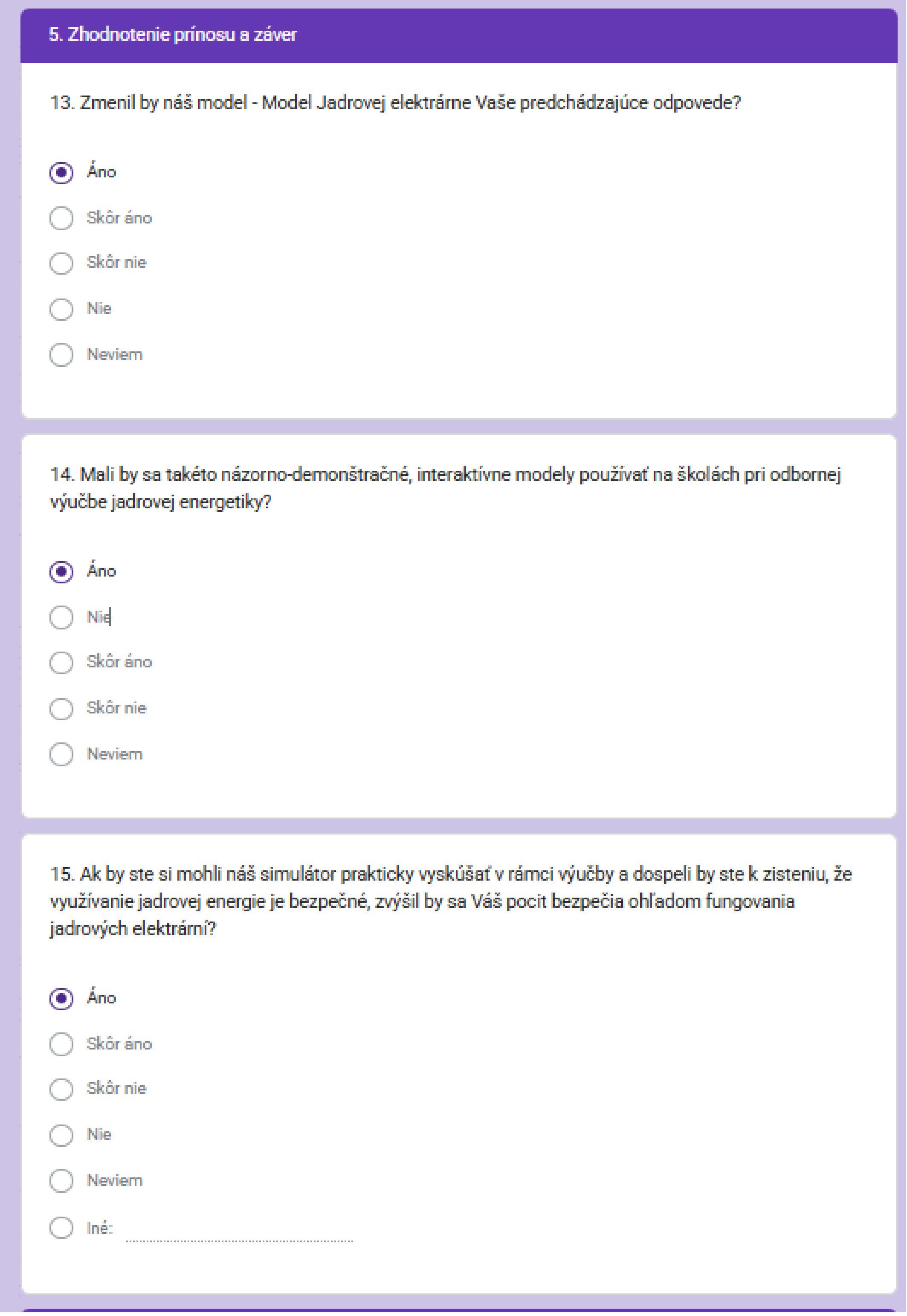
Tento simulátor odkrýva vnútro modernej elektrárne a vysvetľuje cestu čistej energie od reaktora až po chladiace veže.

Čo na modeli uvidíte?

- **Bezpečné srdce:** Vľavo vidíte reaktor a parogenerátory uzavreté v masívnej ochrannej obálke. Model ukazuje, že jadrový proces je bezpečne izolovaný viacerými bariérami z ocele a betónu.
- **Výroba energie (Strojovňa):** V pravej časti uvidíte turbínu a generátor. Ukazuje, ako čistá para roztáča lopatky turbíny a mení mechanickú silu na elektrinu pre tisíce domácností.
- **Oddelené okruhy:** Farebné potrubia demonštrujú kľúčový princíp: voda, ktorá chladí palivo, sa nikdy nemieša s vodou, ktorá poháňa turbínu. Týmto vizuálne potvrdzujeme čistotu celého procesu.
- **Ekologické chladenie:** Dominantné veže v pozadí vypúšťajú do ovzdušia len čistú vodnú paru, nie dym. Model zdôrazňuje, že jadrová energia funguje bez emisií CO2 a chráni našu klímu.

„Náš model mení zložitú technológiu na jasný príbeh. Ukazujeme, že bezpečnosť moderného jadra sa nespolieha na náhodu, ale na nezlyhávajúce fyzikálne zákony."

(Fig. 7)



5. Zhodnotenie prínosu a záver

13. Zmenil by náš model - Model Jadrovej elektrárne Vaše predchádzajúce odpovede?

● Áno
○ Skôr áno
○ Skôr nie
○ Nie
○ Neviem

14. Mali by sa takéto názorno-demonštračné, interaktívne modely používať na školách pri odbornej výučbe jadrovej energetiky?

● Áno
○ Nie
○ Skôr áno
○ Skôr nie
○ Neviem

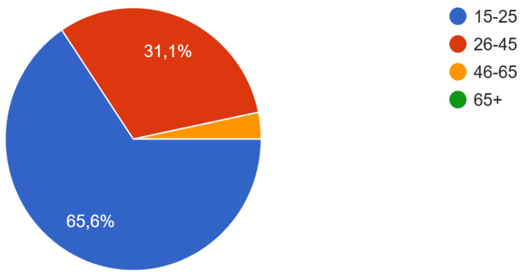
15. Ak by ste si mohli náš simulátor prakticky vyskúšať v rámci výučby a dospeli by ste k zisteniu, že využívanie jadrovej energie je bezpečné, zvýšil by sa Váš pocit bezpečia ohľadom fungovania jadrových elektrární?

● Áno
○ Skôr áno
○ Skôr nie
○ Nie
○ Neviem
○ Iné: ....

(Fig. 8)

1. Vek

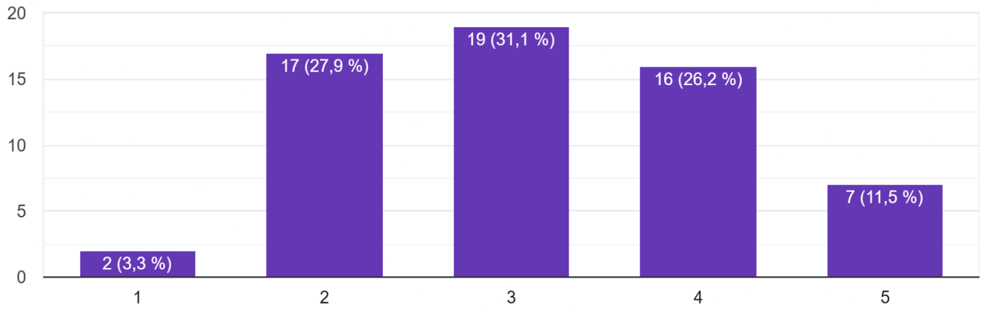
61 odpovedí



(Fig. 9)

2. Moje vedomosti, poznatky, znalosti v oblasti jadrovej energie sú

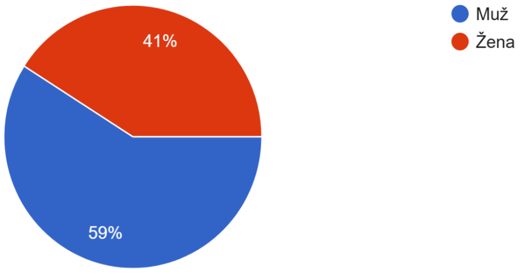
61 odpovedí



(Fig. 10)

3. Pohlavie

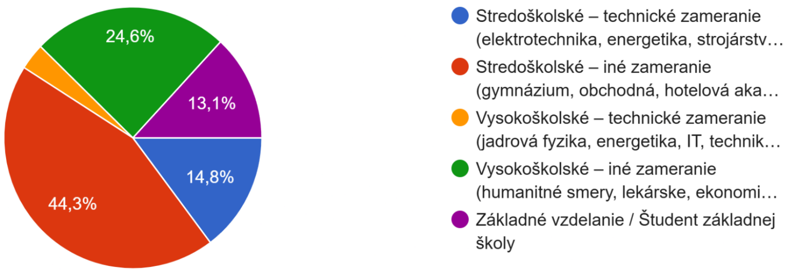
61 odpovedí



(Fig. 11)

4. Aké je Vaše najvyššie dosiahnuté vzdelanie a študijné zameranie?

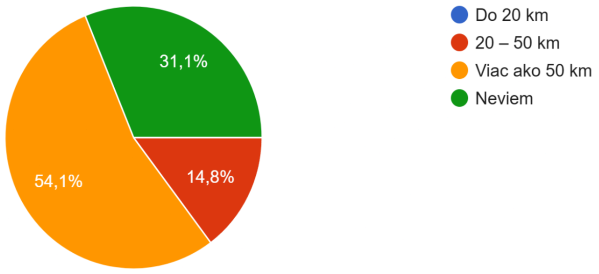
61 odpovedí



(Fig. 12)

5 .Ako ďaleko bývate od najbližšej jadrovej elektrárne (napr. od elektrárne v Mochovciach alebo Jaslovských Bohuniciach)?

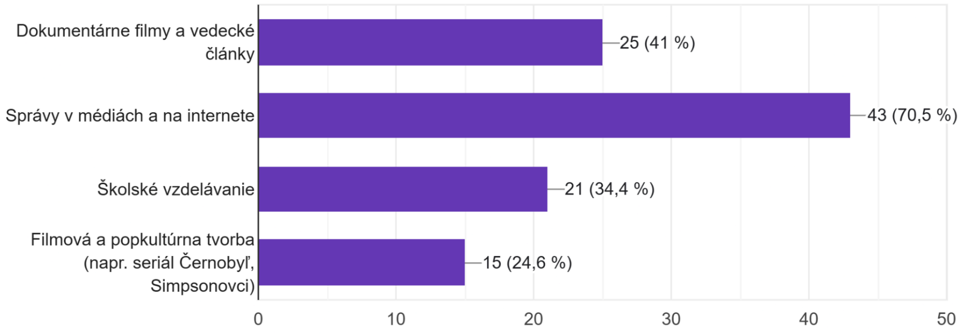
61 odpovedí



(Fig. 13)

6. Ktorý z nasledujúcich uvedených zdrojov najviac ovplyvňuje Váš názor na jadrovú energiu?

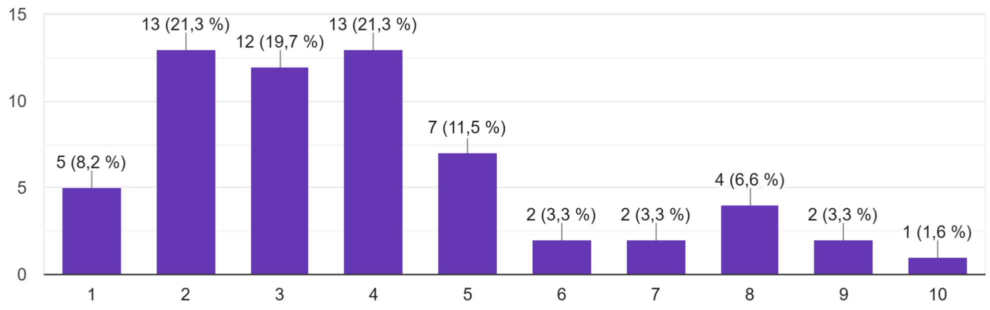
61 odpovedí



(Fig. 14)

7. Nakoľko bezpečná je prevádzka modernej jadrovej elektrárne?

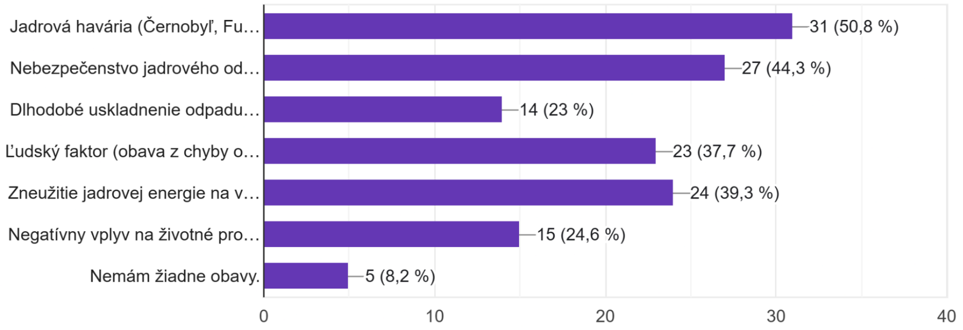
61 odpovedí



(Fig. 15)

8. Ktorá z uvedených možností vo Vás vzbudzuje najväčšie obavy pri slove „jadrová energia“? Môžete označiť viaceré možnosti.

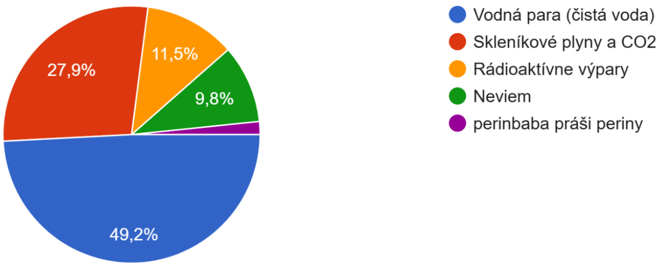
61 odpovedí



(Fig. 16)

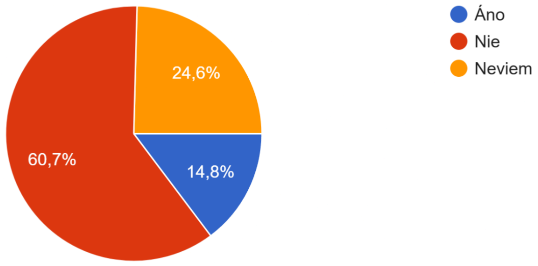
9. Čo podľa Vás tvorí „biely dym“, ktorý vychádza z veľkých chladiacich veží elektrární?

61 odpovedí



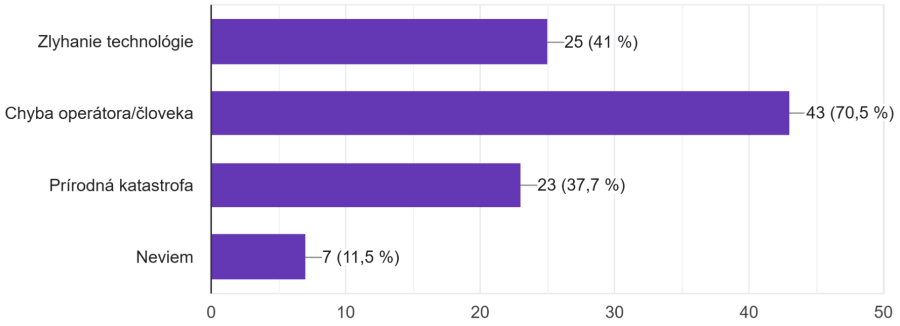
(Fig. 17)

10. Myslíte si, že je možné, aby moderný jadrový reaktor vybuchol ako atómová bomba?
61 odpovedí



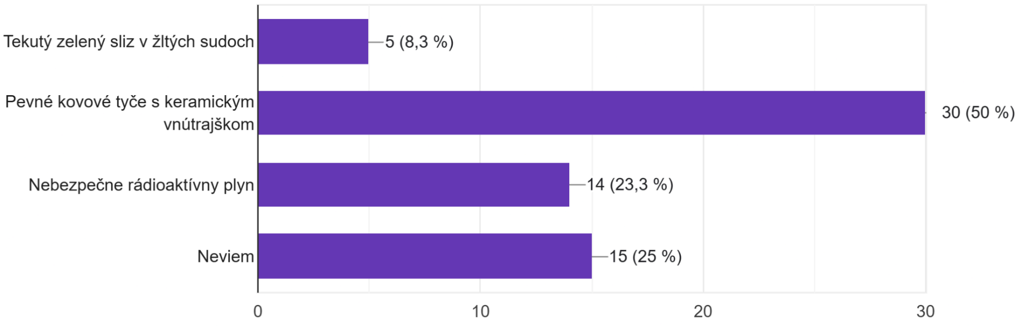
(Fig. 18)

11. Čo bolo hlavnou príčinou zlyhania jadrových reaktorov v minulosti? Môžete označiť viaceré možnosti.
61 odpovedí



(Fig. 19)

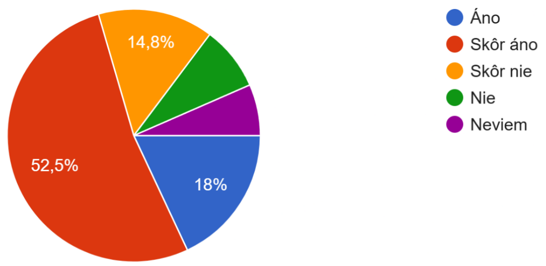
12. V akej forme sa nachádza najnebezpečnejší jadrový odpad (vyhorené palivo)?
60 odpovedí



(Fig. 20)

13. Zmenil by náš model - Model Jadrovej elektrárne Vaše predchádzajúce odpovede?

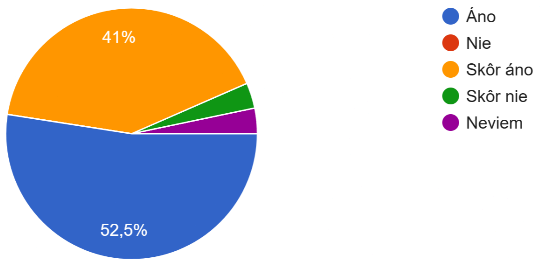
61 odpovedí



(Fig. 21)

14. Mali by sa takéto názorno-demonštračné, interaktívne modely používať na školách pri odbornej výučbe jadrovej energetiky?

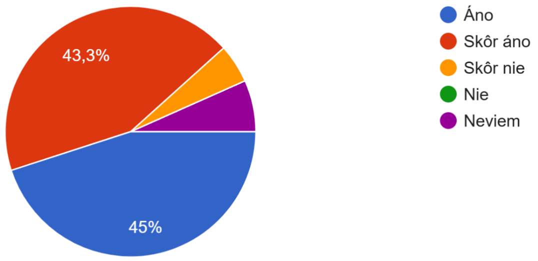
61 odpovedí



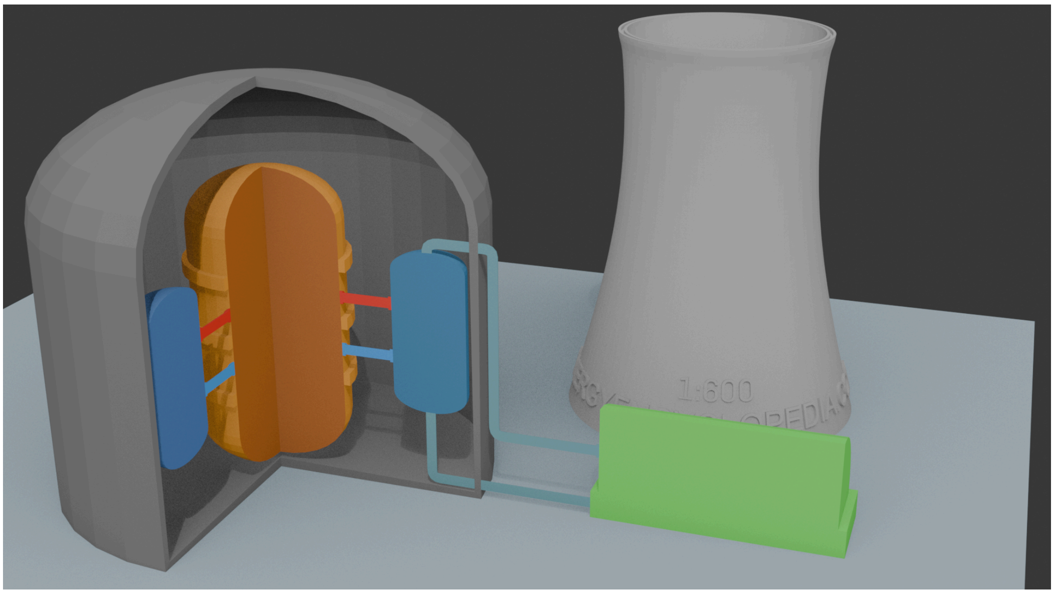
(Fig. 22)

15. Ak by ste si mohli náš simulátor prakticky vyskúšať v rámci výučby a dospeli by ste k zisteniu, že využívanie jadrovej energie je bezpečné, zvýšil by ...ezpečia ohľadom fungovania jadrových elektrární?

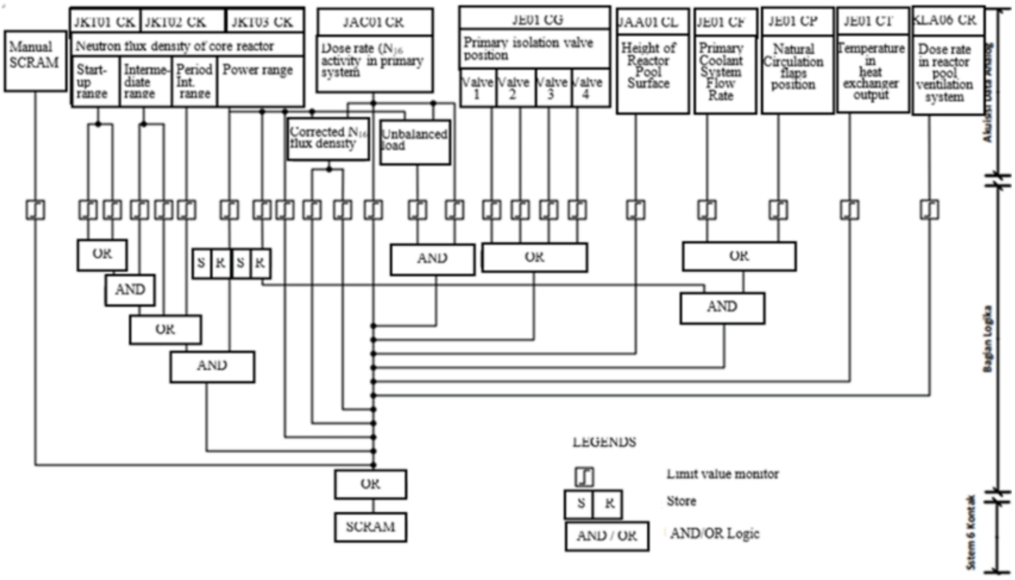
60 odpovedí



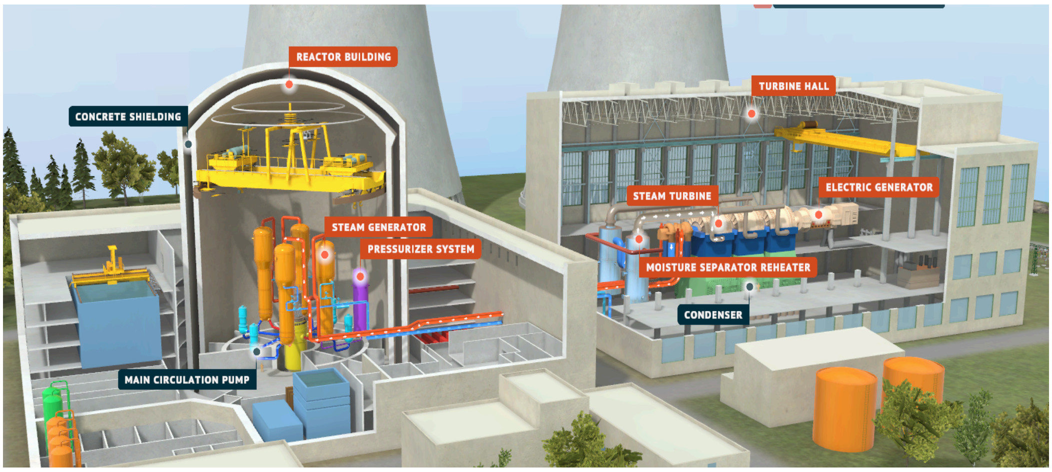
(Fig. 23)



(Fig. 24)[12]



(Fig. 25)[13]



(Fig. 26)[12]

Table 1 Estimated financial budget - Construction

Item	**Estimated cost**
Basic electronics (microcontroller, wiring, breadboard, power supply)	25 - 35 €
Mechanical components (servo motors, control rods)	20 - 30 €
LED strips, LED diodes and other indicators	15 - 25 €
Seven-segment displays and needle gauges	20 - 35 €
Potentiometers, sensors and other electronics	15 - 20 €
3D printing material (reactor body and component construction)	15 - 25 €
Control panel material (enclosure, buttons, switches, connectors)	25 - 40 €
Fastening materials, adhesives, surface finish	10 - 15 €
Subtotal	**145 - 225 €**

Table 2 Estimated financial budget - Operations and logistics

Item	**Estimated cost**
Transport packaging	30 - 50 €
Travel costs for presentation season	40 - 80 €
Printing of information materials and posters for schools	15 - 25 €
Communication with schools (potential administrative fees)	5 - 10 €
Reserve for unforeseen expenses and replacement components	20 - 30 €
Subtotal	**110 - 195 €**

Table 3 Estimated financial budget - Cost per unit

Item	**Estimated cost**
Materials and components (savings from bulk purchasing)	100 - 160 €

Transport packaging per unit	30 - 50 €
Distribution of unit to school	20 - 40 €
Training materials for educators	10 - 15 €
Subtotal	**160 - 265 €**

Table 4 Estimated financial budget - One-Time costs

Item	**Estimated cost**
Development and production of the first prototype	145 - 225 €
Preparation of the teacher training programme	30 - 60 €
Communication with schools and administration	10 - 20 €
Reserve for unforeseen expenses	50 - 80 €
Subtotal	**235 - 385 €**