Radiation in everyday life

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Abstract. Communication surrounding radiation risk is a complex yet important task for the future of nuclear energy. Recent studies show that risk communication in the form of relatable activities provides an accessible route for a layperson to understand scientific information. In this study, everyday activities involving ionising radiation were investigated and used to educate the public on the radiation risk from the nuclear power station, Sizewell C. The results were presented in the form of an interactive website and informative poster. It was found that the UK average annual effective dose from radon gas exceeded the effective dose experienced by a nuclear power station worker. Suggesting that the effective dose from working in a nuclear power station is minimal when compared to the typical radiation dose due to radon gas. Similarly, the findings show that the effective dose from Sizewell C to nearby residents is insignificant when compared to other sources of ionising radiation. The responses from the survey, measuring attitudes towards nuclear energy, suggested that the website and poster were successful in educating the public and reducing fear surrounding nuclear energy. The responses also highlighted the need for further investigation into the risks associated with nuclear disasters and nuclear waste.

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3. Personal Contribution

I was responsible for the research on the radioactivity of coffee, radon levels across the United Kingdom and holidays to Cornwall. As project manager I was responsible for the project plan, primary liaison between the team and our supervisors, and ensuring our team remained motivated. I was also co-creator of the numerical tool in Python, alongside Max Talberg and assisted the construction of the research survey alongside Miles Pearce.

4. Introduction

4.1. Communicating Science

Educating and informing the public effectively about science can be challenging. The complexity of scientific information can alienate members of the public, reducing their engagement and interest. Despite this, the UK public have an appetite to learn from scientific information [1]. A 2019 study, conducted by the Department of Business, Energy & Industrial Strategy, found that 49% of the sample felt that scientists put in 'too little effort' when it comes to informing the public [1] suggesting a need for greater engagement between these two parties. The survey also found that there was a decrease from 47% in 2014, to 38% of people who felt 'very or fairly well informed' about nuclear power. These findings suggest a need for further intervention to combat the declining knowledge surrounding nuclear energy.

Communicating radiation risk is a complex yet important task. Successful nuclear risk communication to the public poses particular challenges due to contrasting and differing views from the nuclear industry and media, as well as the negative public perception heightened by past nuclear disasters. This negative perception has been observed through research findings which found that people perceived radioactivity originating from nuclear sources disproportionately. The findings show that individuals associated radiation from nuclear power and nuclear waste as high risk when compared to other sources of radiation such as x-ray scans and natural radiation [2]. Despite this, it has been found that educating people on radiation risk can reduce their negative perceptions and fears [3].

Frameworks have been developed and introduced to ensure successful communication. A workshop held by the Society of Radiological Protection highlighted the aims that radiation communication must achieve. These included the need to inform and educate, dispel myths, build trust, and inspire future generations [4]. Careful consideration must also be made when deciding the tool to facilitate this communication. Social media is an effective medium to distribute information to a large audience quickly. However, communication via social media is also vulnerable to misinformation and the creation of sensationalised stories. For example, a survey conducted by OFCOM found that 28% of their participants had come across misleading or false information about coronavirus [5]. Once misinformation has spread, it becomes difficult to correct the false claims.

Placing radiation risk into perspective through comparing it to other risks can help people contextualise the severity [2]. Key evidence shows that the communication of radiation risk, in relation to everyday life [6], is a successful method to help the public quantify this risk. A previous study in communicating the risk to the local residents after the Fukushima nuclear disaster is an example of this [6]. The study highlighted a successful program which educated residents about the impacts of the incident on their livelihood and farming activities. A main aspect of the program was the residents' involvement. Their concerns were gathered and the Japanese Ministry of Education, utilised this to create a tailored booklet, titled "Information booklet for returnees" [6]. The booklet addressed their concerns through comparing the radiation exposure to typical everyday activities. To supplement this resource, additional face-to-face sessions were held with healthcare professionals, increasing public engagement. A similar project took place in the UK by EDF Energy. The project aimed to reduce concerns surrounding the deposition of dredging material near Cardiff, which was originally sourced near the Hinkley Point nuclear plants [7]. The public concern triggered a discussion in the Welsh Assembly and an engagement campaign was created in response to this. The campaign drew comparisons between the radiation exposure from the dredging material to everyday items and activities to demonstrate the negligible risk this had to the public.

4.2 Nuclear Power and Sources of Radiation

4.2.1 Nuclear Power

Combating climate change and the drive to reduce carbon emissions has been a key challenge for our government and many international bodies across the globe. The motivation to reduce carbon emissions is clearly stated by the Intergovernmental Panel on Climate Change (IPCC). They warn that global warming must not surpass '1.5°C above pre-industrial levels' to prevent the devastating effects caused by climate change [8]. To achieve this goal, the UK Government has committed to its own Net Zero Strategy [9]. A key pledge is to rely on clean, British-made electricity in the future and by 2035 they aim to power the UK with only clean and renewable resources [9]. The pledges emphasise the need for continued support of future energy generation projects that use these renewable and nuclear sources. The UK Government hopes to achieve this goal through utilising nuclear energy, evidenced through the introduction of a £120 million 'Future of Nuclear Enabling Fund' and a £100 million funding pledge to support the development of a new nuclear power station, Sizewell C [9].

The growth of nuclear power stations has been steady since 1956 [10]. As of today, the UK has nuclear power stations across the country consisting of 14 advanced gas-cooled reactors and 1 pressurised water reactor, which currently resides at the Sizewell B site [11].

Nuclear power stations contribute to radiation exposure in several ways. Stations release radioactive materials into the environment and produce radioactive waste. However, when nuclear accidents occur, this radiation exposure becomes more significant. The devastating nuclear plant disasters in Chernobyl and Fukushima shaped the way people perceive nuclear power today. Both disasters were classified as level 7 incidents, according to the International Nuclear Event Scale. The highest classification on the scale, signifying a 'major incident'. The Fukushima disaster was caused by a tsunami. It damaged 3 active reactors, causing hydrogen explosions within the units, releasing radioactive material into the environment [12]. The 1986 Chernobyl disaster was a result of poor design and safety protocol. It was caused by a disastrous power increase in a reactor, leading to a nuclear fire and explosions [13]. In normal working conditions, nuclear power stations appear to be safe to live near and work in. However, the history of catastrophic nuclear disasters and the likelihood of another remains a consideration when evaluating the risk nuclear power poses to the surrounding environment and residents.

4.2.2 Sources and Units of Radiation

Ionising radiation is the energy released from the natural decay of unstable nuclei or from the excitation of atoms. They can be in the form of particles, such as alpha and beta particles, or waves, such as x-rays and gamma rays [14]. Radiation exposure can be harmful to the human body and can damage healthy cells, resulting in either cell death or modification. Modified cells which are not perfectly repaired may cause further damage and lead to the development of cancerous cells [15].

Although ionising radiation can be harmful, it is a fundamental part of our everyday life. Ionising radiation can be categorised into two types: natural radiation and man-made radiation.

Living on Earth, we are all exposed to varying levels of natural radiation. These are sourced from cosmic rays from space and the sun, terrestrial radionuclides from naturally occurring substances in the Earth's crust, and from our human bodies [15]. Natural radiation is the main source of ionising radiation to humans, and it equates to approximately 82% of our total radiation exposure [16].

The largest contributor to natural radiation comes from radon gas. The radioactive gas is formed as an intermediate during the natural decay of uranium and thorium into lead. The natural decay chains of the radioactive isotopes U-238, U-235 and Th-232 produce the respective radioactive radon isotopes Rn-222 (radon), Rn-219 (actinon) and Rn-220 (thoron) [17]. Due to the significant concentrations of U-238 found in rocks and soil [18], Rn-222 is the main contributor of radiation exposure from radon gas. As the natural decay of U-238 occurs, the produced radon gas emanates from the ground and accumulates in enclosed areas. This results in a much higher concentration of the radioactive gas in people's homes and in underground structures, such as mines and caves [19]. Across the United Kingdom, the level of radon varies. There are a number of radon 'hotspots' as highlighted by a national survey conducted in the 1980s. Most notably Cornwall was found to be an area with significant levels of radon gas [20]. Much like radiation exposure from radon, radiation exposure from cosmic rays changes on location. Cosmic ray radiation varies with atmospheric altitude as the shielding effects from the air are reduced. It also varies with latitude; it is typically higher near the Earth's poles and lowest close to the equator.

Ionising radiation from medicine is the most prevalent source of man-made radiation to humans [21]. Depending on the health condition, ionising radiation is commonly used for medical imaging such as CT scans, or treatment such as radiotherapy. Additional sources of man-made radiation are from fallout from nuclear weapons testing, nuclear power stations, smoke detectors and security x-ray machines.

A study conducted in 2010, by Public Health England, determined the contribution breakdown from sources of radiation exposure to the UK population [20]. The results have been summarised in table 1.

Table 1. Public Health England summary of ionising radiation exposure per caput to the UK population in 2010. [20].

Source of Exposure	Contribution to Total Exposure (%)
Radon and Thoron	48
Medical	16
Terrestrial Gamma Radiation	13
Cosmic Radiation	12
Intakes of Radionuclides (excluding radon)	11
Weapons Fallout	0.2
Occupational	0.02
Discharges	0.01

Radiation exposure can be measured in various ways. One method is to measure the absorbed dose, (in Gy). Absorbed dose is defined as the energy deposited by radiation in a medium per unit mass [22]. As described in equation 1.

$$D_{T,\,R} = \frac{Q}{m}, \tag{1}$$

where $D_{T,R}$ is absorbed dose, in tissue type T, from radiation type R. Q is the energy deposited by radiation, and m is the mass of the medium.

To understand the radiation effects to individual organs in the human body, equivalent dose is used. Equivalent dose takes into account that each radiation type has varying degrees of damage to tissues [22]. It is determined using the absorbed dose and the radiation weighting factor W_R, where radiation weighting factor is 20 for alpha particles, and 1 for x-rays, gamma rays and beta particles. Equivalent dose, H_T, can be expressed as,

$$H_T = \sum_R D_{T,R} W_R \text{ [22].} \tag{2}$$

It can also be useful to understand the effects of radiation to the human body as a whole. The total effective dose to the entire body is a measure of the health impact of ionising radiation to an individual. It provides an indication of the health risks due to radiation exposure, often used in relation to radiation protection. It considers that each organ is affected by radiation differently. The total effective dose, E, can be expressed as the summation of the equivalent doses to different organs,

$$E = \sum_T H_T W_T \text{ [22],} \tag{3}$$

where W_T is the tissue weighting factor for each tissue or organ. The summation of all tissue weighting factors for all the tissues in the body is equal to 1.

4.3 Our Project Background and Aim

Sizewell C is a new nuclear power station, set to be constructed on the Suffolk coastline. It is planned to incorporate two EPR reactors and to be an almost identical replica of the already approved nuclear power station, Hinkley Point C in Somerset [23]. The power station has recently received financial backing from the UK government and once constructed, it is estimated to supply enough energy to power six million homes in the United Kingdom [24].

To support the upcoming development of Sizewell C and Britain's journey to Net Zero, we proposed a project focussing on communicating the associated radiation risk. There have been past related literature measuring the success of communicating radiation risk to the public. One campaign sought to educate returning residents post Fukushima nuclear disaster [6] and another to educate the Welsh population and Welsh Assembly about the negligible risk posed from a nearby dredging project [7]. Both studies emphasised the need to communicate risk in the context of simple everyday activities as it allows a layperson to understand complex information. The latter study highlighted the need for 'simple and factual' information, enabling the reader to form their opinion rather than being influenced by emotive language. Both studies were considered when devising the communication methods used to communicate radiation risk.

The aim of this project was to create digital tools and deliver clear, and inclusive messaging surrounding radiation risk that could be understood by a member of the public. This was achieved through researching relatable, everyday activities that involved ionising radiation. To quantify the risk nuclear power stations pose to the public, comparative links were made through contrasting these activities to the typical radiation doses experienced by those living near and working in a nuclear power station. With the goal to understand the radiation risk nuclear power stations pose to the public and how digital communication tools can facilitate communicating this risk.

5. Methods

5.1 Radioactivity in Everyday Activities

Everyday activities were chosen based on their level of radioactivity and relatability to the typical British citizen. It was ensured that a range of different activities were included to provide breadth to the public, demonstrating that radiation is present in many activities. Research was conducted to determine effective dose, through undertaking desktop reviews of already established scientific research and findings. The source and author of the research was investigated to ensure it is not subject to publication bias and the findings were compared with previous studies to confirm they were consistent.

To understand how the effective doses compared to the doses sourced from nuclear power stations, the effective dose for a typical nuclear power station worker and for someone living 1km from Sizewell C was used. Data was provided through the Sizewell C 'Human Impact Report' [25] and the HSE 'Occupational Exposure to Ionising Radiation' report [26]. To compute the risk the radiation doses had to the public, the UK average total effective dose (2.7mSv) was sourced from the Public Health England study and was used to draw comparisons between our findings [20].

5.1.1 Radioactivity in Food and Drinks

The effective dose from consuming coffee, bananas, and beer, was determined through researching the activity concentrations of the present radionuclides. The activity concentration can be converted into effective dose if the mass or volume ingested, and the ingested dose coefficient (conversion factor) are both known. The ingested dose coefficient considers radiation and tissue weighting factors, and the functions within the human body [27]. Common ingested dose coefficients can be found in table 2.

As suggested by the ICRP (International Commission of Radiological Protection), the total effective dose, E, was determined using the dose equation for the intake of radionuclides,

$$E = \sum E_i = \sum AC_i V_i e_i \text{ [27]}, \tag{4}$$

where E_i is the effective dose from the nuclide, i, (in Sv), AC_i is the ingested activity concentration, V_i is the volume or mass ingested, and e_i is the ingested dose coefficient.

Table 2. Summary of radionuclide ingested dose coefficients from ICRP Publication 119 [28]

Radionuclide	Ingested Dose Coefficient, e_i, (Sv Bq^{-1})
K-40	6.2×10^{-9}
Pb-214	1.4×10^{-10}
Bi-214	1.1×10^{-10}
Pb-212	5.9×10^{-9}
U-238	4.5×10^{-8}
U-234	4.9×10^{-8}
Po-210	1.2×10^{-6}

5.1.2 Radioactivity in Medical Scans

To estimate the effective dose from common x-ray scans, the absorbed dose to different tissues due to x-ray beams was investigated. Absorbed dose was converted to effective dose using equation 3. The tissue weighting factors required for this study were sourced from the ICRP 103 publication [29]. Two x-ray scans were researched, intra-oral dental x-rays, the most common dental x-ray and a 2D wrist x-ray, often used to diagnose wrist fractures.

5.1.3 Radioactivity in Commercial Flights

To determine the effective dose from a typical short haul flight taken by UK citizens, radiation dosage rates were investigated. Data was sourced from the CARI-6 computer program, a model developed by the Federal Aviation Administration Civil Aerospace Medical Institute [30]. The CARI-6 model calculates radiation dose from cosmic ray radiation experienced by an adult whilst travelling in an aircraft. The model considers the altitude of the flight and determines radiation dosage (in h/mSv), the length of time required for the passenger to receive 1 mSv of radiation. Radiation dosage data was generated for altitudes between 8230m to 14630m and latitude of 30°. Radiation dosage was converted to radiation dose per hour in transit (in mSv/h) and plotted against altitude. The relationship between altitude and radiation dose per hour exhibited a power relationship. The data was extrapolated for altitudes between 3800m to 8230m to enable radiation dose to be found for flight paths travelling at lower altitudes. The effective dose for a flight travelling at 4877m, the maximum altitude of a flight from London to Ibiza [31], was found using the extrapolated graph and taking the typical flight duration to be 2 hours and 30/40 minutes. In this study, it was assumed that the take-off and landing times were negligible compared to the total flight time, therefore assuming altitude for the entire flight was constant and was cruising at the maximum altitude. The results from the CARI-6 model can be found in figure 1.

5.1.4 Radioactive Radon Levels Across the United Kingdom

The annual effective dose, due to naturally occurring radon gas, in the United Kingdom was found for each county. As suggested by the ICRP, the effective dose, E, from an exposure to radon was determined using equation 5,

$$E = R\,T\,e_R \text{ [32]}, \tag{5}$$

where R is the average radon level in the respective county (in Bq m^{-3}), T is the time spent indoors (in h), and e_R is the radon dose coefficient (in Sv m^3 Bq^{-1} h^{-1}). Average radon level for each county was found using the Public Health UK, "Radon in Homes" report [33]. The radon dose coefficient for inhaled radon gas was taken to be 6.7x 10^{-6} mSv·m^{3}Bq^{-1}h^{-1} as recommended by the ICRP Publication 137 [34]. It was assumed that the average adult spends 75% of their time indoors [25], therefore time spent indoors was taken to be 18 hours per day.

Cornwall has significantly higher levels of radioactive radon gas compared to other locations within the United Kingdom [35]. As a result, visiting Cornwall is an area of particular interest when considering additional sources of ionising radiation to the members of the public. The effective dose for spending 3 days in Cornwall, the typical duration of a domestic holiday in the UK [36], was also found using equation 5.

5.2 Communication of Radiation Risk to the Wider Public

To communicate radiation risk, three digital tools were created to be accessible to the members of the public. The first was a digital radiation calculator to calculate the total effective dose from everyday activities, which was developed using Python. The second and third were to provide simple messages to communicate radiation risk in the form an infographic poster and social media campaign. The digital tools were developed with careful consideration of the target audience. The use of language, colour and images were considered to create an engaging, relevant, and informative messaging campaign.

To measure the success of the communication methods, a structured survey was conducted to understand how the participants' perception of nuclear energy and the associated risks changed after interacting with the radiation calculator and infographic poster. The survey questions followed a Likert scale and were designed to include a balance of positive and negative questions to mitigate against acquiescence bias. The questionnaire was completed anonymously and administrated remotely online.

5.2.1 Radiation Calculator

A radiation calculator in the form of a web application, was created using Python and additional packages, Dash and NumPy. The numerical tool was created in three parts: A back-end calculator, front-end user interface, and two datasets. The datasets contained the effective dose of each everyday activity, based on the research previously conducted, and the annual effective dose from radon level, for each county in the United Kingdom.

The front-end user interface was produced with support from Bootswatch themes [37]. The user interface prompted the user to answer questions, asking how often they engage with typical activities, either per week or per year. These inputs are stored on the website and used to output their total effective dose and how this compares to working in or living near a nuclear power station. To provide further visual tools, two graphical outputs were created. The first represented the difference in annual effective dose (from everyday activities) to the exposures experienced due to nuclear power stations. The second graph provided a breakdown of how their activities contributed to their total effective dose in the form of a pie chart.

The radiation calculator was developed with the main colour orange, to provoke emotional responses of optimism and warmth, as well as being visually eye-catching as summarised by the New York City College of Technology [38]. Following guidance from the WHO principles of effective communication [39], it was assumed that the public had little knowledge of radioactivity. With this assumption, additional information boxes were created for each question to provide the public with additional background information. To improve accessibility, simple and clear language throughout the tool was used. The radiation calculator was also made available online and was adjusted to work on mobile devices. Images of the typical questions and outputs from the web application can be visualised in figure 3.

5.2.2 Messaging Campaign

The infographic poster and social media campaign was developed following guidance provided by LSE's 'Guide to Writing Engaging Content' [40]. As the guidance suggested, both the poster and social media campaign included images to improve engagement. The poster was produced with resources supplied from Canva [41]. It consisted of two sections, the first compared the effective dose experienced from living 1km from Sizewell C to doses from typical everyday activities. The second compared the average effective dose experienced from working in a nuclear power plant to the same everyday activities. The social media campaign was developed to include a question and public poll to further increase engagement and instigate discussions related to radiation risk. Extracts from the social media campaign and infographics poster are presented in figure 4.

6. Results

6.1 Radioactivity in Everyday Activities

Radioactivity in Food and Drink

A study investigating the radioactivity of coffee beverages using high resolution gamma spectrometry was analysed [42]. The research paper sampled 18 different coffee brands and found the average activity concentration across the samples to be 15.5 ± 3.5 mBq ml^{-1}, 0.59 ± 0.15 mBq ml^{-1}, 0.70 ± 0.08 mBq ml^{-1}, and 0.55 ± 0.13 mBq ml^{-1}, for K-40, Pb-214, Bi-214, and Pb-212 respectively [42]. For the purpose of this study, activity concentration was converted into ingested activity, by taking volume ingested to be a typical volume of a mug, (300ml [43]). To determine effective dose, ingested dose coefficients were sourced from table 2 for the radionuclides of interest. The results are presented in table 3. Total effective dose for a mug of coffee was found through summing all doses, resulting in a total effective dose of $2.99 \times 10^{-5} \pm 6.5 \times 10^{-6}$ mSv.

Table 3. Radionuclide breakdown in a coffee beverage and associated effective dose from each present nuclide.

Radionuclide	Ingested Activity (in 300ml) (Bq)	Effective Dose (mSv)
K-40	4.65 ± 1.05	$2.88 \times 10^{-5} \pm 6.5 \times 10^{-6}$
Pb-214	0.177 ± 0.045	$2.48 \times 10^{-8} \pm 6.3 \times 10^{-9}$
Bi-214	0.209 ± 0.023	$2.30 \times 10^{-8} \pm 2.6 \times 10^{-9}$
Pb-212	0.164 ± 0.039	$9.68 \times 10^{-7} \pm 2.3 \times 10^{-7}$

The effective dose from consuming a banana was found through investigating the activity concentrations (in Bq kg^{-1}) of present radionuclides. A study found the activity concentrations, using high purity germanium detectors, to be 48.77 Bq kg^{-1} for K-40 and 1.56 Bq kg^{-1} for U-238 [44]. Effective dose was found through taking the mass of a banana to be 100g [45] and ingested dose coefficients for K-40 and U-238 from table 2. The ingested activity per banana and effective dose from the respective radionuclides can be found in table 4. The total effective dose from the contributions from both radionuclides was found to be 3.7×10^{-5} mSv.

Table 4. Radionuclide breakdown in a banana and associated effective dose for each present radionuclide.

Radionuclide	Ingested Activity (in 100g) (Bq)	Effective Dose (mSv)
K-40	4.877	3.02×10^{-5}
U-238	0.156	7.02×10^{-6}

Effective dose from a pint of beer was approximated through analysing a study which determined the activity concentrations in Polish beers, using alpha-spectrometry. The study found the activity concentrations to be 4.63 ± 0.40 mBq dm^{-3}, 4.11 ± 0.56 mBq dm^{-3}, 4.94 ± 0.90 mBq dm^{-3} for Po-210, U-234 and U-238 respectively [46]. Effective dose was determined by taking volume ingested to be 0.568 dm^3, the approximate volume of a pint, and dose coefficients from table 2. The ingested activity and associated effective dose can be found in table 5. Total effective dose from all radionuclides was found to be $3.40 \times 10^{-6} \pm 2.7 \times 10^{-7}$ mSv.

Table 5. Radionuclide breakdown in a pint of beer and associated effective dose for each present radionuclide.

Radionuclide	Ingested Activity (in 568ml) (Bq)	Effective Dose (mSv)
Po-210	$2.63 \times 10^{-3} \pm 2.3 \times 10^{-4}$	$3.16 \times 10^{-6} \pm 2.7 \times 10^{-7}$
U-234	$2.34 \times 10^{-3} \pm 3.2 \times 10^{-4}$	$1.14 \times 10^{-7} \pm 1.6 \times 10^{-8}$
U-238	$2.81 \times 10^{-3} \pm 5.1 \times 10^{-4}$	$1.26 \times 10^{-7} \pm 2.3 \times 10^{-8}$

Radioactivity in Medical Scans

A journal that used the Monte-Carlo methods found the absorbed dose from an intra-oral x-ray scan to be 0.04 mGy and 0.06 mGy for the salivary glands and oral mucosa [47]. Using the associated tissue weighting factors from the ICRP 103, effective dose from an intra-oral dental x-ray was calculated to be 0.002 mSv. The effective dose from a typical wrist x-ray was obtained from a journal [48] which calculated effective dose using recommendations from ICRP 103. Through analysing the absorbed dose to bone marrow, skin, bone surface, lymphatic nodes and muscles in a wrist phantom, (anthropomorphic substitute to a human hand), effective dose was found to be 0.001 mSv.

Commercial Flights

Figure 1 displays the CARI-6 model data, extrapolated for lower altitudes using a power fit. The effective dose was approximated for a short haul flight (London to Ibiza). The effective dose rate at 4877m altitude was approximated to be 0.00055 mSv h^{-1}, resulting in an effective dose for a 2 hour and 30/40 minute to be 0.00133 mSv.

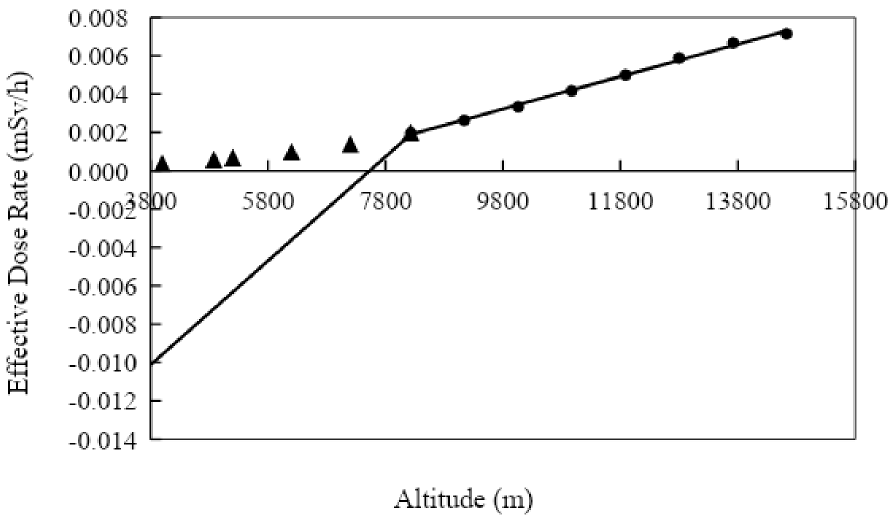

Figure 1. Relationship between effective dose rate and altitude, at a latitude of 30°. The CARI-6 model data was fitted with a power fit, which was extrapolated to extend for altitudes between 3800m to 8230m. CARI-6 model data represented by •, extrapolated data represented by ▲, power fit represented by —.

Radioactive Radon Levels Across the United Kingdom

The highest levels of annual effective dose were observed in the English county, Cornwall, which had an average value of 4.63 mSv y^{-1}. This is consistent with the findings from UK Radon, which states that Cornwall has a radon potential in the largest band [49], >30%. The radon potential is the likelihood that a building has a radon level equal or above the action level of 200 Bq m^{-3}. The action level signifies whether intervention is required to reduce radon levels in homes. The second largest annual effective dose was observed in the Welsh county of Pembrokeshire, which had a value of 2.95 mSv y^{-1}, also consistent with UK Radon findings. The lowest annual effective dose was observed in the Welsh county of Blaenau Gwent, which was calculated to be 0.48 mSv y^{-1}. This is as expected as the radon potential for Blaenau Gwent is between <1% and 1-3%, signifying a very low probability of a home having a radon level equal or above the action level. The annual effective dose from radon, averaged across all UK counties was found to be 1.55 mSv y^{-1}.

The effective dose for staying in Cornwall for 3 days was found using equation 5 and radon dose coefficient of 6.7x 10^{-6} mSv·$m^3Bq^{-1}h^{-1}$. Time spent indoors was taken to be 54 hrs, which assumed the average domestic holiday length was 3 days [36] and the average person spends 75% indoors [25]. Average radon level for Cornwall was taken as 105 Bq m^{-3}, sourced from the Public Heath UK, "Radon in Homes" report. [33]. Effective dose for a short holiday to Cornwall was found to be 0.0379 mSv. A summary of all the effective doses from everyday activities can be found in table 6.

Table 6. Summary of the effective doses from everyday activities.

Activity	Effective Dose (μSv)
Drinking a cup of coffee	0.0299 ± 0.0065
Eating a banana	0.037
Drinking a pint of beer	0.0034 ± 0.0003
Intra-oral dental x-ray	2
Wrist x-ray	1
One-way short haul flight (London to Ibiza)	1.33
3-day holiday to Cornwall	37.9

Table 7. Summary of the annual effective doses from everyday activities, and nuclear power stations in ascending order. Values are contrasted against the typical UK average total dose from all sources of radiation.

Activity	Annual Effective Dose (mSv)
Annual beer consumption	0.00036 ± 0.00003
Wrist x-ray	0.001
One-way short haul flight (London to Ibiza)	0.00133
Intra-oral dental x-ray	0.002
Annual banana consumption	0.0037
Living 1km from Sizewell C	0.013
Annual coffee consumption	0.0218 ± 0.0047
3-day holiday to Cornwall	0.0379
Nuclear power station worker	0.5

UK average radon dose	1.55
UK average total effective dose	2.7

To compare the effective doses from everyday activities to the doses from nuclear power stations, the typical annual consumptions of coffee, bananas and beer were found to determine the approximate annual effective doses. It was found that the average person consumes 2 coffees a day [50], roughly 100 bananas a year [51] and 107 pints of beer a year [52]. Table 7 summarises the annual effective doses from the researched everyday activities, effective dose from nuclear power stations and how these compare to the typical UK public annual dose from all sources of radiation.

6.2 Communication of Radiation Risk to the Wider Public

6.2.1 Digital Tools

The radiation calculator was created to contain 8 questions resulting in 4 different outputs. The outputs are presented in the form of total annual effective dose (from everyday activities), the equivalent expressed in multiples of the annual doses from working in a nuclear power station and living 1km from Sizewell C, and two graphs. A bar chart comparing the effective dose (from everyday activities) to the annual effective doses from nuclear power stations and a pie chart displaying how each activity contributes to the total effective dose (from everyday activities). A schematic of the radiation calculator representing the relationship between the front-end and back-end is shown in figure 2. Images of the front-end user interface can be found in figure 3. Refer to the appendices for access to the radiation calculator and Python code.

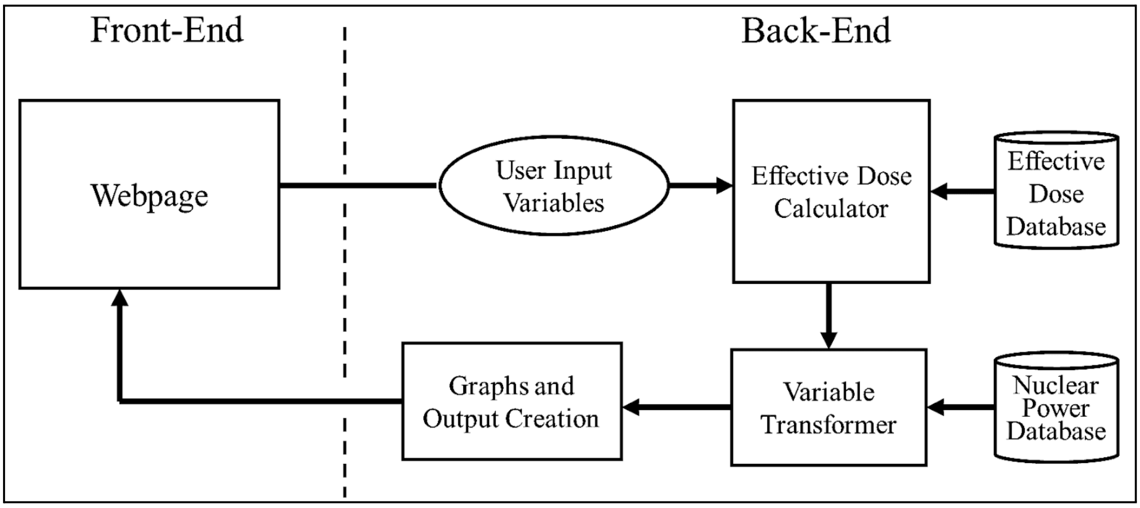

Figure 2. The relationship between the user inputs on the front-end webpage, to the back-end calculator and output creator. The arrow directions indicate the flow of data/information through the radiation calculator.

The infographics poster was created to compare the annual effective dose experienced from working in a nuclear power station such as Sizewell C, and the exposure from living within 1km of Sizewell C to the radiation exposure from everyday activities. An extract from the poster and social media campaign can be visualised in figure 4.

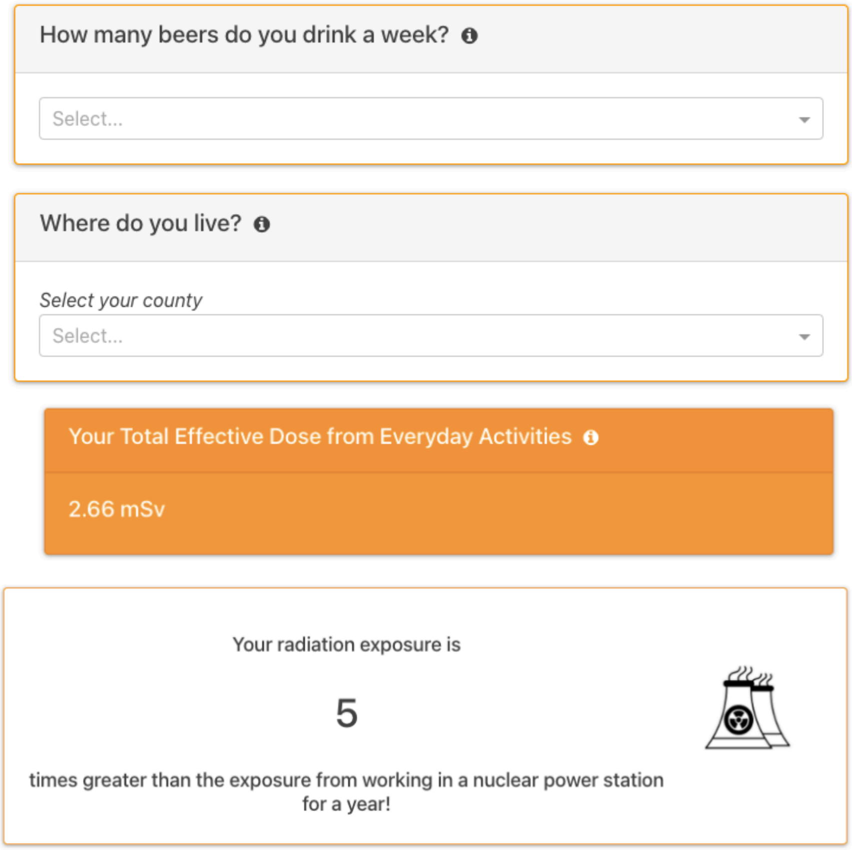

Figure 3. Example of the radiation calculator questions and a typical results output from the user's interaction with the tool.

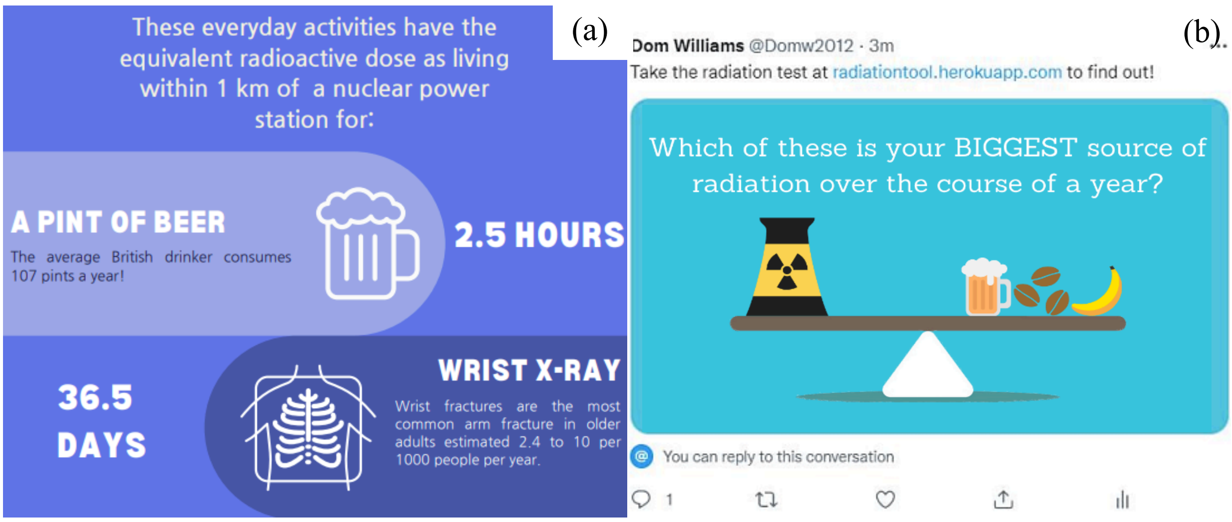

Figure 4. Example of the infographic poster to illustrate the radiological risks from living near Sizewell C (a) and the social media campaign (b). The poster compares the annual effective dose from living 1km away from Sizewell C to the effective dose sourced from beer and a wrist x-ray. The social media post encouraged a discussion surrounding nuclear power stations and prompted viewers to use the radiation calculator.

6.2.2 Impact of Radiation Risk Communication

The survey required participants to answer questions relating to their opinion towards nuclear energy and radiation. They were then prompted to view and interact with the radiation calculator and infographics poster and then complete the same set of questions again. The results from the survey are summarised in figure 5. The sample size consisted of 87 adults: ~55% were aged 18-28, ~10% were aged 29-38, ~21% were aged 49-58, ~9% aged 59-68 and ~5% aged 69 and over.

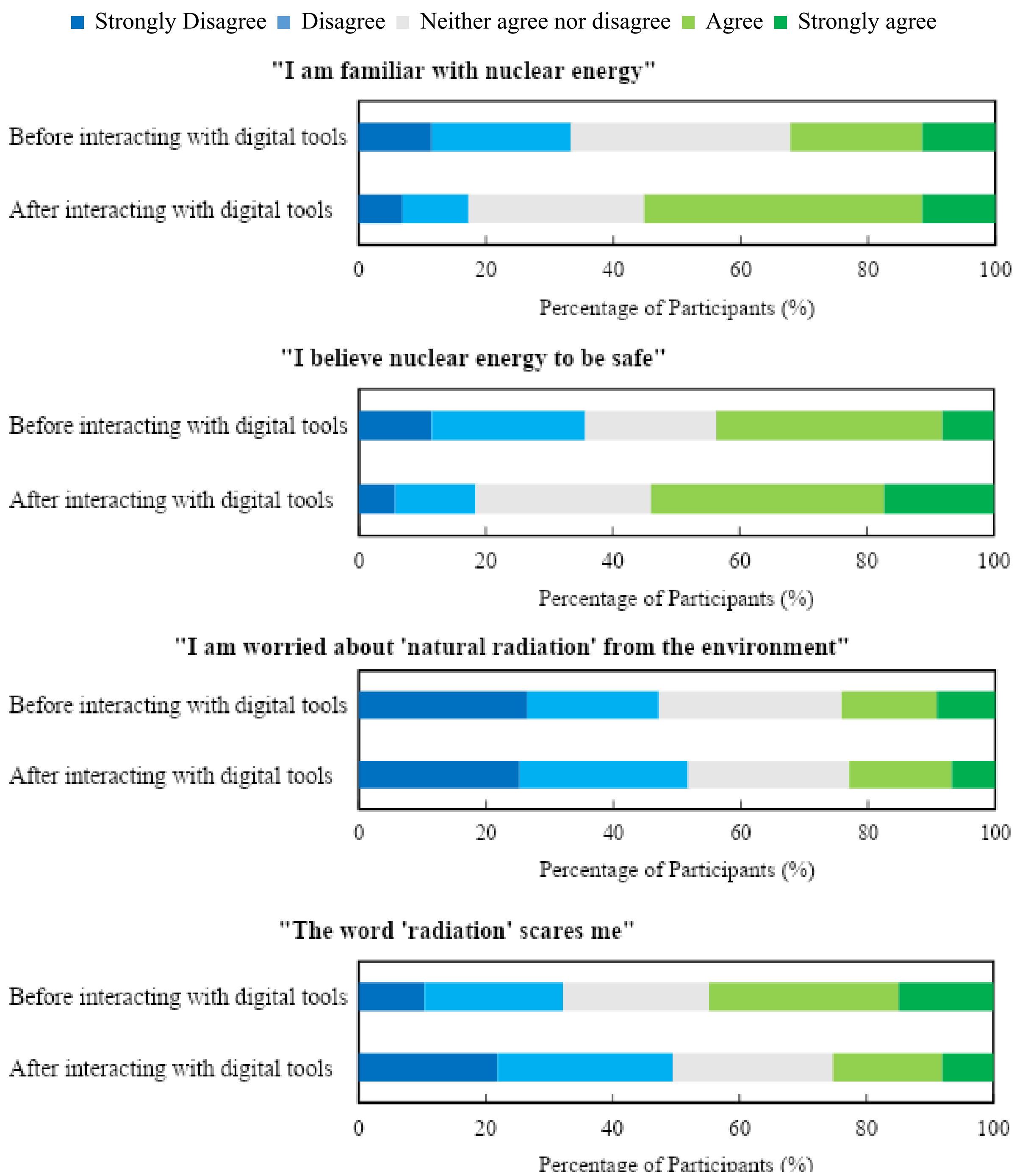

Figure 5. Survey responses related to opinions of nuclear energy and radiation before and after interacting with the radiation calculator and infographics poster. The survey measured how strongly participants agreed or disagreed with the statements shown in bold. Total sample size consisted of 87 adults.

7. Discussion

7.1 Radioactivity in Everyday Activities

The results presented in table 7 indicate consistencies with the radiation exposure contributions summarised by Public Health England, (shown in table 1). The largest investigated effective dose from everyday activities was found to be from radon gas. Consistent with the large contribution radon and thoron have on the public's total exposure. Comparing the researched effective doses to the doses originating from nuclear power stations indicated the relevance of these exposures. Notably, all the investigated effective doses from everyday activities, except dose due to radon gas, were found to be smaller than the average annual effective dose from working in a nuclear power station. Despite this, the dose experienced by a nuclear worker is still below the UK safety limit of 20 mSv per year [26] and below the typical total annual dose experienced by a member of the UK population.

The effective dose from a cup of coffee was consistent with a research paper, which calculated effective dose from Malaysian coffee to be 7.42 x 10^{-5} mSv [53]. The variations in effective dose from food arise from the properties of the specific plants, the soil which they are grown in, and the method used to detect radionuclides. This suggests that an acceptable range for effective dose of a cup of coffee lies between 10^{-5} – 10^{-4} mSv, varying with the coffee brand and country of origin. Assuming the average person consumes 2 coffees a day [50], the estimated annual effective dose from coffee is ~1.7 times larger than the dose received by someone living 1km from Sizewell C. This implies that the effective dose due to the discharges from nuclear power stations to nearby residents is insignificant when compared to the dose from the annual intake of radionuclides in coffee.

The effective dose from consuming a banana was found to be smaller than the widely accepted banana equivalent dose (0.1 μSv) [54]. Another research paper found the banana effective dose due to only K-40 to be 0.002 μSv [55], signifying a large discrepancy between estimated banana effective dose values. The variations in effective doses from bananas is due to the consideration of the absorption of K-40 in the digestion process. A process which is dictated by the level of potassium deficiency in the body [55]. Assuming the average person consumes approximately 100 bananas a year [51], the effective dose from an annual consumption of bananas found in this study is approximately ~3.5 times smaller than the effective dose from living 1km from Sizewell C. Despite this, when considering the typical consumption from other food and drinks combined, it is clear that the total effective from the intake of radionuclides would likely exceed the radiation exposure from residing near Sizewell C.

The radioactivity in beer is largely dependent on the region is it brewed in due to the varying levels of radioactivity of water in different countries. Calculating the effective dose from activity concentrations from Polish beer therefore is not fully representative of beers typically brewed and drunk in the UK. It does, however, provide a reasonable approximation for the typical effective dose from beer required for this project. The effective dose from beer is not widely researched making it is difficult to validate the effective dose found in this study. Through analysing the effective dose from tap water, however, can provide a good indication of the expected effective dose since water is the primary source of radioactivity in beer [46]. A research paper which assumed that 1litre of tap water was consumed per day, found the annual effective dose from UK tap water to be 10 μSv [56]. This results in an effective dose for a pint of water to be 0.048 μSv, a value ~14 times greater than the effective dose found in Polish beer. A journal determining the annual effective dose from Polish tap water, obtained a value of 0.0005 μSv [46] for a pint of water. A value ~100 times smaller than the value found in the UK. This suggests that the effective dose from beer brewed in the UK is expected to be greater than the value obtained from the Polish beer study due to significantly higher level of radioactivity in UK tap water.

Effective dose from an intra-oral dental x-ray was found to be similar to the dose calculated by the Health Protection Agency which used historic NHS absorbed dose data to determine effective dose. The effective dose was estimated to be 0.003 mSv [57] which suggests an acceptable approximation for effective dose from a dental x-ray is between 0.002 – 0.003 mSv. Due to the added dependence on the individual physical traits of the patient and that the NHS data was averaged across different medical centres, the variations in effective dose for an x-ray scan are expected. Typically, members of the public have approximately one dental x-ray a year, therefore the annual effective dose from a dental x-ray does not exceed the annual dose from living near Sizewell C and is significantly lower than the average annual nuclear worker dose.

The effective dose for a 2D wrist x-ray was found to be ~3 times greater than the dose found in the same Health Protection Agency study. They found the average effective dose to be 0.0003 mSv [57]. Despite the variations, the estimates for effective dose from x-ray scans, determined in study, lie close to other published values.

The effective dose from a one-way flight from London to Ibiza did not exceed the doses from working or living near a nuclear power station. However, approximately 10 one-way flights had an equivalent effective dose to the dose experienced from living near Sizewell C. These findings demonstrate that a member of the public who is a frequent flyer, experiences a similar radiation dose from flights to the dose from residing near Sizewell C. The effective dose from a short-haul flight from the UK to Madrid was approximated in a Public Health England report [20]. The study took average dosage rate to be 0.004 mSv h^{-1}, resulting in the effective dose from a one-way flight to be 0.01 mSv. This finding is roughly ~8 times larger than the value found in this study. The variation in effective doses is sourced from the differing flight dosage rates. As flight dosage rate, in this study, was found through extrapolating CARI-6 flight data, further validation is required to verify that the extrapolated dosage rates at lower attitudes are consistent with other research findings. The effective dose from short-haul flights is not widely researched, which created further limitations when trying to verify the results. Despite this, effective dose from a short-haul flight, although it cannot be completely validated, still offers a relatable and illustrative means of communicating radiation dose to the British public.

The effective dose due to radon gas was shown to be significantly higher than other sources of ionising radiation, as previously discussed. Measuring effective dose in this manner presents various limitations. Dose due to radon in each home differs depending on the ventilation habits of the homeowners, the time spent indoors, which season of the year it is, and placement of the radon detector to name a few [58]. As a consequence, using average effective dose by county may provide an over or underestimate to the actual dose experienced by a member of the public living in that region. To understand the radon level in one's home, individual measurements must be taken, which can be achieved through using measurement packs widely available through UK Radon [59]. Despite this, determining the average effective dose, from radon gas, for each UK county provides a personalised means of communicating radiation risk to the public. Estimating effective dose from visiting Cornwall using the current method also has limitations. Although it was found that people averagely spent 75% of their time indoors, this assumption has not been adjusted for behavioural changes during the holidays. However, as time spent indoors is heavily dependent on season and weather, this method provides a good approximation for typical effective doses from radon gas. The effective dose from visiting Cornwall for a day was found to be approximately equivalent to the annual effective dose experienced from living within 1km to Sizewell C. Staying 40 days in Cornwall is approximately equivalent to the average annual effective dose experienced by a nuclear power station worker. Similarly, the UK average dose due to radon was found to be approximately ~3 times larger than the annual dose of a nuclear worker. Both findings suggest the doses from nuclear power stations are minimal when compared to doses due to naturally occurring radon gas.

7.2 Communication of Radiation Risk to the Wider Public

7.2.1 Digital Tools

The three digital tools offered simple and concise messages to communicate radiation risk to the public. The radiation calculator provided an interactive tool to encourage users to explore sources of radiation and how these compare to radiation doses from nuclear power stations. Providing a personalised approach to risk communication. The social media campaign supported the discussion surrounding the risks using seesaw imagery, placing nuclear power in the context of activities which are commonly considered to be low risk. The infographics poster presented concise, factual information for the reader, allowing them to independently decide whether they felt at risk, free from emotive language. A method previously adopted by the campaign to inform the Welsh population about risks from dredging material [7]. Our decision to include the effective dose from flights, coffee, bananas and medical scans was also adopted by this campaign [7] signifying the effectiveness of using these day-to-day activities to demonstrate radiation risk.

When it comes to the distribution of information, posters are not typically circulated digitally due to their static nature. Other forms of digital media tend to carry the user through an interactive journey of information, exploiting the advantages of digital communication methods. Despite this limitation, as a tool, it remains a powerful method in displaying holistic information, as it is limited to an easily digestible page.

Creating the tools digitally provided the opportunity to distribute the information widely and quickly. However, the lack of in-person engagement presents limitations to this method of communication. In-person interactions offer the opportunity to tailor communications to directly meet the needs of listeners. It also provides the opportunity to address any confusion and misinterpretation, mitigating against the spread of misinformation. Incorporating an in-person aspect to this messaging campaign would enhance the quality of the engagement and communication with the user.

Previous comments regarding the radiation calculator suggest the need to include further day-to-day activities that involve ionising radiation to increase the accessibility of the tool. The inclusion of radioactivity in beer is an effective comparison for some demographics, however not all members of the public drink alcohol. Including further activities such as the effective dose from smoking cigarettes or medical sources of radiation such as radiotherapy and additional medical scans could increase the relatability of the calculator however risks overcomplicating the tool. It is important to note that the inclusion of other activities, such as bananas are highly applicable to a wide audience and fit the aim of the project.

The response from the survey suggests that the public still have remaining concerns regarding nuclear radiation risk. A further improvement to the messaging campaign could be achieved through using the survey responses to further tailor the radiation calculator and infographics poster. A method previously utilised in the “Information booklet for returnees” [6] created after the Fukushima nuclear disaster. For example, including the risk posed from nuclear waste and previous nuclear disasters would address the specific concerns that arose from the survey.

7.2.2 Impact of Radiation Risk Communication

The responses from the survey suggested attitudes to nuclear energy are varied. Those who agreed or strongly agreed with nuclear energy being safe before using the digital tools, justified their reasoning with the heavy and ‘robust’ laws put in place to regulate the nuclear power industry. Others also commented on the ‘low’ probability of devasting incidents and the fact that energy generation, using nuclear power, has been adopted in other countries across the globe, inferring its safety. Those who disagreed or strongly disagreed to nuclear energy being safe, made comments towards the fact that ‘radiation’ is involved and that past disasters suggested its unsafety. A notable finding was that the nuclear disaster in Chernobyl appeared 6 times in the comments, suggesting that past nuclear incidents have a large influence on people’s current opinion of nuclear energy. The proportion of participants who still believed nuclear energy to be unsafe after interacting with the digital tools, justified their answers with the prospect of potential nuclear disasters, and the problems surrounding nuclear waste disposal. These findings suggest that further research into the probability of nuclear disasters and a focus on the risks associated with nuclear waste would ensure further concerns of the public are addressed.

When participants were asked if they felt that they were familiar with nuclear energy, before interacting with the tool, ~33% of 18–38 year-olds, covering the Gen Z or Millennial participants, stated they disagreed or strongly disagreed. Contrasting with the older generation of 49+ year-olds, approximately ~46% stated they disagreed or strongly disagreed. The findings suggest that there may be a generation gap related to nuclear education. Further sampling would be required to validate this assumption due to the disproportionate sample sizes in each age category.

When participants were asked whether ‘natural radiation’ worried them ~75.9% strongly disagreed, disagreed or neither agreed nor disagreed with this statement. This proportion increased to ~77.0% after interacting with the tools. These findings support the conclusion that typically the public view radiation from natural sources as low risk [2].

The impact of the radiation calculator and infographics poster can be measured through comparing the participants initial and final responses from the survey. Before interacting with the digital tools, ~35.6% of participants strongly disagreed or disagreed with the statement that they believed nuclear energy to be safe. After interacting with the tools, this proportion declined to ~18.4%. Similarly, the proportion of those who answered strongly agree, or agree to the same question increased from ~43.7% to ~54.0%. Further impact can also be observed. Before interaction with the digital tools, ~44.8% of participants agreed or strongly agreed to the statement that the word ‘radiation’ scared them. In contrast, after interacting with the tools, this proportion declined to ~25.3%. The value of education in reducing fear and negative perception surrounding nuclear power plants was also observed from a study conducted by the US Energy Department Low-Dose Radiation Research Program [3]. Similarly, when participants were asked if they felt ‘familiar’ with nuclear energy, the proportion of participants who strongly agreed or agreed increased from ~32.2% to ~55.2%. This suggests that these digital tools were successful in informing and educating the public.

The disproportionate distribution of ages and demographics in the sample means a causal connection between the digital tools and their ability to increase knowledge and reduce fear towards nuclear energy cannot be fully made. To gain a fully representative view of the UK public's opinion, further sampling across the older age groups is required. Additionally, it is important to note that of those who took part, majority of participants were university students or were close relatives of university students.

Although the use of Likert scale style questions offers simplicity, it can also produce false results. For example, participants will tend to not select the extreme values on the scale and be more inclined to choose neutral responses [60]. Extra care must be taken to gather people's attitudes towards this subject, which can often be solved through conducting the research face-to-face to capture the participants' emotions.

Following the findings from the survey, it is clear that digital tools tailored for a non-scientific audience can be used to educate and inform the public. However, the proportion of participants who selected neither agree nor disagree suggests that some participants remain unsure about topics highlighted within the survey. Further intervention and education would be required to improve radiation risk communication to the wider public.

8. Conclusion

Various everyday activities involving ionising radiation were researched and compared to the effective doses from living near or working in a nuclear power station. The effective dose from drinking a cup of coffee, was found to be, $2.99 \times 10^{-5} \pm 6.5 \times 10^{-6}$ mSv, 3.7×10^{-5} mSv for eating a banana, $3.40 \times 10^{-6} \pm 2.7 \times 10^{-7}$ mSv for drinking a pint of beer, 0.001 mSv for a wrist x-ray, and 0.002 mSv for an intra-oral dental x-ray. The effective dose from holiday related activities were found to be 1.33×10^{-3} mSv and 0.0379 mSv for a short-haul flight (London to Ibiza) and a 3-day holiday to Cornwall, respectively.

When compared to the effective doses from living near and working in a nuclear power station, the results suggest that the nuclear discharges from Sizewell C to the public are insignificant when compared to other sources of ionising radiation. It was found that most investigated everyday activities had an effective dose smaller than the average annual dose experienced by a nuclear worker. However, the UK average radon dose was found to exceed this. Suggesting that the effective dose resulting from working in nuclear power station is minimal when compared to the radiation exposure sourced from naturally occurring radon gas.

Digital tools aimed to educate and inform the public about radiation risk were created in the form of a radiation calculator, infographics poster and social media campaign. It has been demonstrated that these digital tools do provide a means of educating the public about radiation risk as suggested from the outcomes from the survey. It was found that the proportion of participants who disagreed or strongly disagreed that nuclear power was 'safe' decreased after interacting with the tools. Additionally, the proportion who strongly agreed or agreed that the word 'radiation' scared them decreased after interacting with the tools showing that a campaign such as this can be successful at reducing fear and negative perceptions.

Additional research into nuclear waste and the frequency of nuclear disasters would provide a greater understanding of the risk nuclear power stations pose to the public. Including this information in the digital tools, would also address the concerns that arose from survey comments and may reduce additional fears surrounding nuclear energy. Repeating the survey with a larger sample size with a greater age and demographic distribution would provide a more representative view on the public's attitudes towards nuclear energy. Equally, conducting the survey face-to-face would offer the opportunity to gain further insight into the public's attitudes as well as reducing the chance of participants misinterpreting information.

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Appendices

1 Radon Level Across the UK

Table 8. Average radon level and average annual effective radon dose for counties in the United Kingdom. Radon level data was sourced from the 'Radon in Homes' report [33].

County	Average Radon Level ($Bq\ m^{-3}$) [33]	Average Annual Effective Dose ($mSv\ y^{-1}$)
Buckinghamshire	36	1.59
Cambridgeshire	27	1.19
Cornwall	105	4.63
Cumbria	61	2.69
Derbyshire	49	2.16
Devon	54	2.38
Dorset	29	1.28
East Sussex	34	1.50
Essex	19	0.84
Gloucestershire	56	2.47
Hampshire	32	1.41
Hertfordshire	30	1.32
Kent	27	1.19
Lancashire	48	2.11
Leicestershire	40	1.76
Lincolnshire	52	2.29
Norfolk	25	1.10
North Yorkshire	45	1.98
Northamptonshire	40	1.76
Nottinghamshire	38	1.67
Oxfordshire	60	2.64
Somerset	42	1.85
Staffordshire	40	1.76
Suffolk	25	1.10
Surrey	23	1.01
Warwickshire	34	1.50
West Sussex	34	1.50
Worcestershire	31	1.37
Greater London	18	0.79
Greater Manchester	17	0.75
Merseyside	12	0.53
South Yorkshire	28	1.23
Tyne and Wear	13	0.57

West Midlands	18	0.79
West Yorkshire	32	1.41
Blaenau Gwent	11	0.48
Bridgend	33	1.45
Caerphilly	17	0.75
Cardiff	33	1.45
Carmarthenshire	46	2.03
Ceredigion	50	2.20
Conwy	42	1.85
Denbighshire	63	2.78
Flintshire	60	2.64
Gwynedd	36	1.59
Isle of Anglesey	58	2.55
Merthyr Tydfil	25	1.10
Monmouthshire	41	1.81
Neath Port Talbot	15	0.66
Newport	23	1.01
Pembrokeshire	67	2.95
Powys	48	2.11
Rhondda Cynon Taf	19	0.84
Swansea	29	1.28
Torfaen	17	0.75
Vale of Glamorgan	54	2.38
Wrexham	43	1.89
Antrim and Newtownabbey	18	0.79
Armagh, Banbridge and Craigavon	33	1.45
Belfast	19	0.84
Causeway Coast and Glens	27	1.19
Derry and Strabane	51	2.25
Fermanagh and Omagh	37	1.63

2 Radiation Calculator

2.1 Sources of Additional Effective Dose Data

The tool included further questions regarding other everyday activities containing ionising radiation. The data was sourced from the following locations. Effective dose from a typical long-haul flight, (London to Singapore) was sourced from the Australian Radiation Protection and Nuclear Safety Agency [30]. Cosmic background radiation in the UK was found in the Public Health England, Ionising Radiation 2010 report [20] and effective dose from CT scans was sourced from the UK Government dose comparison findings [61].

2.2 Access to the Radiation Calculator and Respective Python Code and Datasets

The radiation calculator can be accessed via the URL: https://radiationtool.herokuapp.com/

The Python code, associated datasets and images can also be accessed on GitHub, via the URL:https://github.com/MaxTalberg/PH30096