Estimating carbon footprint of paper and Internet voting

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Abstract. This paper compares the carbon footprint of paper voting in polling stations with the emissions of remote vote casting via the Internet. We identify the process steps with the most significant emissions in terms of CO_2 equivalent, design a methodology to quantify these emissions and give a comparative analysis based on the example of the Estonian parliamentary elections of 2023. Our results show that paper voting has about 180 times higher carbon footprint, owing largely to the need to transport the voters to the polling stations and back.

Keywords: Paper voting · Internet voting · Carbon footprint.

1 Introduction

To guarantee generality of the elections, the voters must be provided with convenient and easily accessible voting methods. Voting in a specified location (polling station) on a specified date (election day) is one of the typical options, but there are also a number of other complementary methods. Many countries allow votes to be cast in polling stations during the advance voting period, and it is also common to provide the option to vote via mail. In some cases, it may even be possible to cast votes via phone, fax or Internet [8].

While positively impacting availability, multi-channel elections also pose several challenges. To retain uniformity, care has to be taken that only one vote per voter gets counted even if the voter attempted to use several channels [13]. Even though, in principle, electronic channels provide cheaper ways of voting, full paper-based infrastructure is still typically kept running, increasing the total cost of operations [12].

In this paper, we take a different approach to comparing alternative channels of vote casting, and instead of the direct monetary cost, we consider their environmental impact.

To the best of our knowledge, the environmental impact of voting methods has not been explicitly studied. However, there are a few related studies on general governance issues.

In 2011, Zampou and Pramatari assessed paper-based public services provided in Greece and estimated their carbon footprint. They argued that the footprint could be lowered by digitalising the services but did not give precise estimates on the respective gain [19].

The same year, Larsen and Hertwich estimated the carbon footprint of various public services offered by the Norwegian county of Sogn og Fjordane [14]. Unsurprisingly, the largest CO_2 equivalent emissions were connected to the transportation and energy supply.

In 2015, Tehnunen and Penntinen identified that moving from paper-based invoicing to electronic invoicing decreases the carbon footprint of one invoice lifecycle by 63%. The greatest effect came from the elimination of unnecessary manual work, while material and transportation were significant factors as well [17].

In 2022, Zioło *et al.* studied the correlation between the E-Government Development Index (EGDI) and several societal development aspects (including environmental) based on data from 26 European countries. The correlation between the EGDI and the environmental parameters was positive and statistically significant but lower than the correlation between EGDI and other social and economic parameters [20].

Even though digital technologies allow to lower the amounts of paper and ink required, they may come with a significant environmental footprint of their own due to increased computational demand. In 2009 it was estimated that, as a result of one Google search query, 0.2 grams of CO_2 equivalent is emitted[3]. Depending on the methodology used, watching 1 hour of an HD movie over Netflix is estimated to emit $432 \ldots 1681$g of CO_2 equivalent [3]. In 2015, data centres were estimated to contribute 2% of global greenhouse gas emissions, equal to the emissions from global aviation [11]. Bitcoin mining is estimated to contribute almost the same amount [5].

Thus the question of whether the introduction of digital technologies actually lowers or raises the carbon footprint is a non-trivial one and needs to be addressed in a particular context. In this paper, we will concentrate on voting and attempt to assess how the transition from paper to remote electronic vote casting would affect the environmental impact.

We will be using Estonia as the case study as there the numbers of paper *vs* Internet voters have been roughly equal since 2019 [7], and the share of Internet voters slightly surpassed 50% during the 2023 parliamentary elections[4]. Being a small country with good infrastructure and efficient data management processes, the raw data required to estimate the environmental impact was also relatively easy to obtain.

Our paper makes two main contributions. First, we develop a methodology to assess the carbon footprint of different voting methods (see Section 2). Secondly, we apply this methodology to two specific methods – paper voting (Section 3) and Internet voting (Section 4). A lot of the base data that we were able to obtain for our computations is approximate. Hence the final numbers should

[3] `https://googleblog.blogspot.com/2009/01/powering-google-search.html`
[4] `https://rk2023.valimised.ee/en/participation/index.html`

also be treated as estimates. However, we feel that our general approach to the methodology is valuable in its own right as well.

2 Methodology

The fundamental document for assessment of environmental impact is the Kyoto Protocol, which was first adopted on 11 December 1997 and entered into force on 16 February 2005.[5] The Kyoto Protocol states the approach to assess environmental impact in terms of greenhouse gas emissions but does not specify a concrete methodology for it. Of course, several methodologies have been proposed by international organisations in the following years of implementation.

There are seven gases reported under the Kyoto Protocol framework: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). However, these are often re-computed into CO_2 equivalent (also noted as CO_2e) that can be determined by multiplying the share of each gas by its respective factor of Global Warming Potential [2].

US-based World Resources Institute has developed Greenhouse Gas (GHG) Protocol used by the leading industrial players in the US and also some other countries.[6] Their methodology is built around the product life cycle and thus can not be directly used on something like voting, which is a state service rather than a product. However, the GHG Protocol also has guidelines for cities to report their greenhouse gas emissions [2], and several aspects of these guidelines are applicable to our research.

European Environment Agency (EEA) released a report presenting different perspectives on accounting for greenhouse gas emissions [1]. The report focuses principally on emissions of CO_2e as there is the most information available on carbon dioxide. In addition, focusing on one compound also makes it easier to understand the differences between the different emission perspectives. The report lays down three common approaches to comparatively assess these emissions in different countries. These approaches are based on territorial, production and consumption information, respectively.

Our methodology can be viewed as a combination of GHG Protocol's City reporting and EEA's consumption-based approach. Accordingly, we defined the following phases for our methodology.

1. **Boundary definition** We concentrate on the actions directly related to the preparation and conducting of the elections. The amortised general costs (like building the community houses or schools where voting took place) are not taken into account. Also, in this research, we only look at the activities that relate to only paper or Internet voting, but not both.
2. **Identification of the key activities** There are several dimensions that help us to identify the key activities. The GHG protocol [2] categorises

[5] `https://unfccc.int/documents/2409`
[6] `https://ghgprotocol.org/`

emission sources into three large scopes: stationery (buildings, manufacturing, etc.), transportation, and waste management (disposal). As the next step of the research, all three scopes were instantiated with the appropriate activities from the voting processes [12].

3. **Assessment of the CO_2e emissions of the identified activities** This phase consisted of two major steps. First, we conducted expert interviews with the Estonian Electoral Management Body (EMB), the Estonian State Information Agency and the vendor of the Estonian Internet voting system. These institutions provided estimates of various parameters concerning the process steps (e.g. what distance needed to be covered to distribute the ballot sheets to the polling stations or the power consumption of the i-voting servers). We also used the results of the regular post-elections survey performed in Estonia. At the last stage, we estimated the carbon footprint of the identified steps, presenting the results in terms of CO_2e emissions per vote.

3 Paper voting processes

In our analysis, we will be using the carbon footprint of travel measured in grams of CO_2e per passenger kilometre as estimated by Our World in Data.[7] An excerpt of their dataset relevant to our study is given in Table 1.

Table 1. Estimates of CO_2e emission per passenger kilometer

Mode of transportation	CO_2e emission (g)
Car	192
Bus	105

However, travelling on foot also has an impact on CO_2e emissions as the energy used when walking has to be replaced by food, the production of which has a certain carbon footprint.

Cohen and Heberger assess that assuming an average diet, walking emits about four times less CO_2e than driving a car [4]. Thus, we will use the value $\frac{192}{4} = 48\frac{\text{g}}{\text{km}}$ for the average CO_2e emission of walking.

In the following, we will estimate the CO_2e emission per paper vote, of which there were 301620 given in the 2023 Estonian parliamentary elections.[8]

3.1 Printing the ballots

According to the EMB, the number of printed ballots was somewhat lower than the number of eligible voters (966129), as it was predictable that many people

[7] `https://ourworldindata.org/grapher/carbon-footprint-travel-mode`
[8] `https://rk2023.valimised.ee/en/participation/index.html`

would vote online. So we estimate that about 900000 ballots were printed. Ballot sheets used in Estonia are relatively small, about A5 in size. Thus we estimate that for the parliamentary elections of 2023, approximately 450000 sheets of A4 paper were used for ballots.

Also, about 11000 sheets of A4 paper were used to print out candidate lists at the polling stations. Adding the paper used for information leaflets and advertisement of polling stations, we estimate the amount of paper used to be about 500000 A4.

According to Diaz and Arroja [6], the CO_2e footprint of a sheet of A4 office paper is between 4.26 and 4.74 grams depending on the exact type and manufacturing standards of the production. The ballot paper had an FSC-C022692 responsible forestry certificate, so we will use the lower end of the Diaz and Arroja estimate interval, concluding that production of the ballot paper emitted about $500000 \cdot 4.26\text{g} = 2.13\text{t}$ of CO_2e. Dividing by 301620 paper voters, this amounts to approximately 7.1g per vote.

3.2 Transporting the ballots to the polling stations and back

The geographical coordinates of the polling stations of the Estonian 2023 parliamentary elections were freely available as a part of the map application designed for the elections.[9] According to the information obtained from the EMB, the ballots were first taken to the county centres and then transported to the polling stations from there.

Thus, we first estimated the distances from Tallinn to the county centres and then from the county centres to the polling stations. To find the shortest routes, we used Openrouteservice[10] together with the routingpy utility.[11] As we needed to get an estimate for the distances, we assumed that the ballots were distributed following a star-like network graph, where the county centres acted as the distribution hubs.

As a result, we found that the total distance needed to the transport the ballots to the polling stations was about 14000km. Taking into account the need to later also transport the ballots back to the district centres for counting, we estimate that the total distance covered was about 28000km.[12]

This result is aligned with the estimate by Krimmer *et al.* [12] that 40743.4km of transportation was required for about 400000 paper votes given during the Estonian local municipal elections of 2017.

[9] `https://jsk.valimised.ee/geojson/RK_2023.geojson`
[10] `https://openrouteservice.org/`
[11] `https://routingpy.readthedocs.io/en/latest/`
[12] The sum of distances from Tallinn to county centres was about 2300km. Even though the ballots were not taken back to Tallinn, there were still computers and other equipment that needed transportation back, so we decided to account also for this part of the trip both ways.

Assuming that most of the ballots were transported by cars or minivans, we take $192\frac{\text{g}}{\text{km}}$ from Table 1 for the CO_2e emission. Thus, we get

$$28000\text{km} \cdot 192\frac{\text{g}}{\text{km}} \approx 5.38\text{t}$$

for the total emission. Dividing this by 301620 paper voters, we estimate the average CO_2e emission of ballot transportation per vote to be about 17.8g.

3.3 Transporting the voters and polling station staff to the polling stations and back

After the 2023 parliamentary elections of Estonia, a population-wide study was conducted, engaging 1001 voters.[13] At our request, the coordinator of the study included questions concerning the mode and time of transportation to the polling station. For 404 polling station voters in the sample, the distribution of answers is given in Table 2. The table shows the number and percentage of voters using a specific form of transport, the average time it took them to get to the polling station and back, and the percentage of persons who only took this trip for voting *vs* people who also did something else (shopping, visiting a friend, etc.).

Table 2. Transportation to and from the polling station

Mode of transport	# of voters	Percentage	Average time	Only voting	Other chores
Car	191	47.3%	25.9 min	41.0%	59.0%
By foot	186	46.0%	18.7 min	57.6%	42.4%
Public transport	21	5.2%	50.0 min	43.0%	57.0%
Bicycle	2	0.5%	20.0 min	–	–
Not specified	4	1%	–	–	–

Only 2 out of the 1001 respondents said they took a bike ride. Also, no one claimed to have taken an electric scooter (even though this option was provided for an answer). The timing can explain such low shares, as the 2023 parliamentary elections of Estonia took place in late February and early March when the weather conditions did not support biking or riding an electric scooter. We expect the respective numbers to be higher for the European Parliament elections taking place in May 2024. As the number of bicycle riders was so small, we do not take them into account in this study.

During the 2023 elections, there were 301620 paper votes cast. According to Table 2, we estimate that $0.473 \cdot 301620 \approx 142700$ voters went to the polling station by car. It took them 25.9 minutes on average. Assuming an average speed of $60\frac{\text{km}}{\text{h}}$, this translates to a trip of 25.9km on average. The CO_2e footprint of

[13] It was actually an event in a long series of studies, organized regularly after elections by the Tartu University Johan Skytte Institute of Political Studies. The interviews were conducted both via phone and in the form of a web-based questionnaire.

1km of travel by car is about 192 grams, resulting in about 4970 grams of CO_2e emission per trip.

Out of the 142700 voters who took a car, $0.41 \cdot 142700 \approx 58500$ made the trip only for voting, and $0.59 \cdot 142700 \approx 84200$ also did something else. Accounting for the other chores, we use the weight 0.5 for the latter group, amounting to

$$58500 \cdot 4970\text{g} + 0.5 \cdot 84200 \cdot 4970\text{g} \approx 500\text{t}$$

of CO_2e emission for all the voters using the car. Dividing by 301620 paper voters, this amounts to approximately 1660g per vote.

Similarly, we estimate that out of the 301620 paper voters, $0.052 \cdot 301620 \approx 15700$ took public transport. It took them 50 minutes on average, which we again translated to 50km using the average estimated speed of $60\frac{\text{km}}{\text{h}}$. The CO_2e footprint of 1km of travel by bus (which is the predominant mode of public transport in Estonia) is about 105 grams, resulting in about 5250 grams of CO_2e emission per trip.

Out of the 15700 voters who took public transport, $0.43 \cdot 15700 \approx 6750$ made the trip only for voting, and $0.57 \cdot 15700 \approx 8950$ also did something else. Again, using the weight 0.5 for the latter group, we estimate the amount of CO_2e emission for all the public transport users to be

$$6750 \cdot 5250\text{g} + 0.5 \cdot 8950 \cdot 5250\text{g} \approx 59\text{t}.$$

Dividing by 301620 paper voters, this amounts to approximately 195g per vote.

For the voters who went to the polling station on foot, we estimate that there were about $0.46 \cdot 301620 \approx 138700$ of them. It took them 18.7 minutes on average, which we translated to 1.56km using the average estimated speed of $5\frac{\text{km}}{\text{h}}$. The CO_2e footprint of 1km of walking is about 48 grams, resulting in about 74.9 grams of CO_2e emission per walk.

Out of the 138700 voters who took a walk, $0.576 \cdot 138700 \approx 79900$ only went to vote, and $0.424 \cdot 138700 \approx 58800$ also did something else. Again, using the weight 0.5 for the latter group, we estimate the amount of CO_2e emission for all the walkers to be

$$79900 \cdot 74.9\text{g} + 0.5 \cdot 58800 \cdot 74.9\text{g} \approx 8.2\text{t}.$$

Dividing by 301620 paper voters, this amounts to approximately 27.1g per vote.

All in all, transportation of paper voters to the polling station and back gives rise to about $1660 + 195 + 27.1 \approx 1880$g of emission per vote in terms of CO_2e.

There is also a carbon footprint associated with transporting the polling station staff to and from the polling stations. There were 484 polling stations established for the 2023 Estonian parliamentary elections. Assuming 4 persons per polling station, we estimate the total personnel to be about 1940 people. This forms about 0.64% of the total number of paper voters. Hence we estimate the CO_2e emission caused by the transport of the polling station staff to be 0.64% of 1880 or about 12g per vote.

3.4 Transportation for the home voting

Krimmer *et al.* [12] estimated that in the 2017 local municipal elections of Estonia, 24273.4 km of travel was required to support home voting. The Estonian EMB was unable to give a similar estimate for the 2023 parliamentary elections.

Thus we will use an approximation based on the observation that in 2017, the distance required for home voting was $\frac{24273.4}{40743.4} \approx 60\%$ of the distance covered for distributing the ballots. Based on our above estimate that the CO_2e emission coming from ballot transport was 17.8g per vote, we assess that the corresponding quantity for the home voting would be about 10.7g.

However, we also have to take into account that the share of Internet voters in Estonia has risen from the 31.7% in 2017 [7] to 50.9% in 2023.[14] This is an increase of about 1.6 times, and we estimate that the need for home voting has decreased accordingly. Thus our final estimate is $\frac{10.7\text{g}}{1.6} \approx 6.7$g of CO_2e emission. Note that we are still considering this footprint per all the paper votes given.

3.5 Running the polling stations

According to the information received from the EMB, during the 2023 Estonian parliamentary elections, there were 484 polling stations altogether. Out of these there were

- 76 stations in the premises of local municipalities,
- 102 stations in community centers,
- 100 stations in cultural establishments,
- 35 stations in libraries,
- 121 stations in schools,
- 28 stations in shopping centres, and
- 22 stations in other buildings.

One of the 22 stations in the latter category was a 300m^2 tent set up in the centre of Tartu. This is noteworthy because, during the voting period of 27 February – 5 March 2023, it was still winter, with the outside temperatures varying between $-10°$ and $0°$ Celsius. The tent was heated using diesel heaters, and the total fuel consumption was approximately 2500 litres, according to the data we obtained from the Tartu city government. CO_2e emission from diesel combustion is approximately 2500 grams per litre, and it is about the same for both mineral and biodiesel.[15] Altogether, heating the tent contributed to about 6.25 tons of CO_2e emission. As there were 301620 paper votes cast, heating this tent alone contributed 20.7 grams of CO_2e emission per vote.

In general, it is very difficult to estimate CO_2e emissions related to the energy consumption occurring as a result of running the polling stations. As we saw

[14] `https://rk2023.valimised.ee/en/detailed-voting-result/index.html`

[15] `https://www.forestresearch.gov.uk/tools-and-resources/fthr/biomass-energy-resources/reference-biomass/facts-figures/carbon-emissions-of-different-fuels/`

above, the vast majority of the buildings have some other continuous use and would be heated anyway. We know that there is some extra energy consumption due to elections as e.g. the temperature in schools is typically lowered for the weekends but not for election Sunday. However, identifying the share of extra energy consumption occurring due to voting is very challenging.

In this paper, we propose an indirect methodology based on the general CO_2e emissions from public services. We use the estimates given by Larsen and Hertwich [14]. According to their calculations, the yearly CO_2e emission attributed to transportation is about 26600 tons in the case of the Norwegian county of Sogn og Fjordane, which has a temperature similar to Estonia. On the other hand, the yearly CO_2e emission attributed to electricity and heating is about 4500 tons. Thus, we estimate that in Sognog Fjordane the electricity and heating emissions are about $\frac{4500}{26600} \approx 17\%$ of the emission occurring as a result of transport.[16]

Taking the estimated transportation emission to be 1880g per vote as computed above, we find that the total emission stemming from running the polling stations is about $0.17 \cdot 1880\text{g} \approx 320\text{g}$ per paper vote. Adding the 20.7g spent on just one tent in Tartu, we get the final estimate of about 340g of CO_2e emission per vote. Note that given the climatic conditions in Estonia, the carbon footprint of heating in winter is definitely higher compared to other seasons. Parliamentary elections happening in late February and early March are hence a more extreme case compared to the local municipal elections taking place in mid-October and European Parliament elections taking place in late May.

3.6 Disposing of the ballots

Paper ballots are counted manually at the polling stations, and afterwards, they need to be stored for at least one month. We estimate that neither of these procedures adds a significant amount of CO_2e emission.

Once all the disputes are resolved, the ballots are destroyed. Our enquiry to the EMB revealed that the destruction of the paper ballots is the responsibility of each district, and there are no centrally imposed rules on how the paper ballots

[16] Of course, the energy production and consumption profiles of Estonia and Norway are different. In Estonia, the largest share of produced energy in winter is spent on heating the buildings, and this energy is mostly delivered in the form of district heating. In Norway, the predominant form of energy is electricity, which is used for heating as well. Norwegian electricity is produced mainly by hydroelectric power plants with relatively low CO_2e emissions. 58.3% of the district heating energy in Estonia, on the other hand, is produced from wood chips. This method of energy production can be considered carbon neutral or even have a slightly negative emission [15]. Thus, the overall comparison of the CO_2e balance is not necessarily too far off. The exact share of space heating *vs* general electricity consumption during the 2023 Estonian parliamentary elections would require a detailed analysis of all the polling stations, but the complete data for this analysis was not available to the authors.

have to be disposed of.[17] In Tartu (which is one of the largest districts), for example, the ballots are shredded, and then the remains are sent to recycling.

While we can assume that shredding is the standard practice for destroying ballots, we do not have complete data concerning what is done with the remains everywhere in Estonia. In general, there are two options to what can happen to the shredded paper: it can be sent to recycling, or it can be mixed with regular waste and sent to a landfill[18]. We will analyse these two possibilities in more detail.

Ximenes *et al.* studied the greenhouse gas emissions from landfills and found that, over time, one gram of shredded copy paper emits on average 326ml of methane [18]. The density of methane is $0.657\frac{\mathrm{kg}}{\mathrm{m}^3}$ (given the temperature of 25°C and pressure of 1atm). Therefore, over time, $0.657 \cdot 0.000326 \approx 0.00021$kg of methane is emitted from one gram of shredded copy paper, which is equivalent to 0.005kg of CO_2e emission according to the Greenhouse Gas Equivalencies Calculator[19]. As stated in Section 3.1, about 500000 A4 paper sheets were used during the 2023 Estonian parliamentary elections, and the approximate weight of one A4 paper sheet is 5g. Thus, dumping paper sheets into a landfill would generate about $500000 \cdot 0.005 \cdot 5 = 12500$kg of biogenic CO_2e emission.

According to the Greenhouse Gases Equivalencies Calculator – Calculations and References[20], for every short ton (equivalent to 907.185kg) of unspecified waste recycled instead of landfilling, CO_2e emission is reduced by 2.89 metric tons. Given the approximate weight of one A4 paper sheet as 5g, the weight of 500000 paper sheets is 2.5t, which means that recycling instead of landfilling could lower the CO_2e emission by an estimated amount of

$$\frac{2.89 \cdot 2.5}{0.907185} \approx 7.96\mathrm{t}.$$

A more detailed methodology was proposed by Merrild *et al.* [16]. They provided estimates of CO_2e emissions for upstream processing of waste paper ($1.3 \ldots 29$kg of CO_2e per tonne of waste paper), direct waste management ($2.7 \ldots 9.4$kg of CO_2e per tonne of waste paper), and downstream processing, i.e., reprocessing of sorted waste paper ($-4392 \ldots 1464$kg of CO_2e per tonne of waste paper). The large range provided for the downstream processing is caused by different assumptions on the effects of recycling.

Three cases were considered in [16]. In the first case, recycling does not affect paper production (resulting in the $488 \ldots 1464$kg of CO_2e emission per tonne of waste paper). In the second case, recycling reduces paper production, which can reduce CO_2e emissions ($-1269 \ldots 390$kg of CO_2e per tonne of waste paper). In

[17] In our analysis, we assume that other paper materials, like candidate lists and advertising materials, will also receive the same treatment as the ballots.

[18] Part of the waste sent to a landfill may be burned to get energy, thereby reducing the amount of fossil fuel that needs to be burned. We do not cover this aspect due to the lack of data.

[19] `https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator`

[20] `https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references`

the third case, it is assumed that due to recycling, less wood is used for producing paper, and instead, the wood is used to replace fossil fuel energy (resulting in $-4392 \ldots -1854$kg of CO_2e emission per tonne of waste paper).

The third case holds quite well for Estonia, where wood is used both for paper production and for generating electricity by mixing it with oil shale. Thus, we took an average of the range presented in the third case, which gives an estimated emission of -3123kg of CO_2e per tonne of recycled waste paper. The weight of 500000 paper sheets is 2.5t, resulting in approximately -7.8t of emission, which is close to the estimate provided by the Greenhouse Gases Equivalencies Calculator. Dividing by 301620 paper voters, this amounts to approximately -25.8g of CO_2e emission per vote.

3.7 Summary of CO2e emissions for paper voting

Table 4 gives an overview of CO_2e emissions for paper voting. The table shows that the transportation of voters had the biggest influence on the CO_2e emission per vote. Discussion regarding the results is provided in Section 5.

Table 3. Summary of the CO_2e emissions for paper voting

Parameter	CO_2e emission per vote (g)
Paper for the ballots and candidate lists	7.1
Transporting ballots to the polling stations and back	17.8
Transport required for the home voters	6.7
Transporting voters to the polling stations and back	1880
Transporting the polling station staff	12
Running the polling stations (electricity, heating)	340
Disposing of the ballots	-25.8
Total:	≈ 2240

4 Internet voting processes

The environmental impact of Internet voting is primarily connected to the power consumption of computers involved in the various stages of the process (development, running the servers and client applications). Thus we will calculate most of the emissions via the energy consumed. For conversion, we will use the estimate that producing one kWh of energy causes 464g of CO_2e emission in Estonia.[21]

We will estimate the CO_2e emission per Internet vote (i-vote), of which there were 312181 given in the 2023 parliamentary elections.[22]

[21] We used Our World in Data estimate from 2022, as the data for 2023 was not yet available. `https://ourworldindata.org/grapher/carbon-intensity-electricity?tab=chart&country=~EST`

[22] `https://rk2023.valimised.ee/en/participation/index.html`

4.1 Software development

According to the information obtained from the software vendor, development efforts targeted towards the Internet voting of the Estonian 2023 parliamentary elections spanned over roughly 1000 hours. Assuming 100W as average power consumption of a developer machine, approximately 100kWh of energy was required for development.

This amounts to

$$\frac{100\text{kWh} \cdot 464\frac{\text{g}}{\text{kWh}}}{312181} \approx 0.15\text{g}$$

of CO_2e emission per i-vote.

To run the test environment, Amazon t3.small hosting based in Stockholm was used for about 57500 hours. Using the AWS carbon footprint estimator[23], this gave rise to about 63000g of CO_2e emission, which is about 0.2g per i-vote.

All in all, we estimate the total CO_2e footprint of the software development to be 0.35g per i-vote.

4.2 Running the servers

According to the information received from the Estonian State Information Agency, the server side of the Estonian Internet voting system is divided into a number of services running on approximately 160 virtual machines. These machines were deployed for the whole duration of the preparation, testing and running of the elections, with the period spanning across four months. An average monthly cost of a virtual machine was estimated to be 3.2 euros (including VAT). Thus the total electricity cost of running the servers for the 2023 parliamentary elections can be estimated as $160 \cdot 4 \cdot 3.2 \approx 2050$ euros.

The average price of one kWh of electricity from November 2022 to February 2023 on the Nord Pool market was about 17.3 cents before taxes[24]. Adding the transmission cost and renewable energy supplement ($5.7\frac{\text{cent}}{\text{kWh}}$ altogether) and the VAT (20%), we get approximately $27.6\frac{\text{cent}}{\text{kWh}}$ as an end-user cost. Thus the estimated energy consumption of running the servers for Internet voting was

$$\frac{2050\text{eur}}{27.6\frac{\text{cent}}{\text{kWh}}} \approx 7430\text{kWh}.$$

Using the above estimate that producing one kWh of energy causes 464g of CO_2e emission in Estonia, we obtain the total carbon footprint to be about 3.4t of CO_2e. Dividing by the 312181 i-votes, we obtain the final emission to be about 11g of CO_2e per i-vote.

[23] https://engineering.teads.com/sustainability/carbon-footprint-estimator-for-aws-instances/

[24] https://www.energia.ee/en/era/elekter/elektriturg

4.3 Running the client applications

According to the study by Paršovs *et al.*, the average time it takes an Estonian i-voter to cast a vote has varied between 140.3 and 193 seconds in different election events [10,9]. Assuming 50W as a power consumption of an average household PC during voting and 167 seconds as an average length of a voting session, we obtain $50\text{W} \cdot 167\text{s} = 8350\text{Ws} \approx 2.3\text{Wh}$ worth of energy spent on casting one vote. As a result, the carbon footprint of casting one i-vote is, on average, $2.3\text{Wh} \cdot 0.464\frac{\text{g}}{\text{Wh}} \approx 1.1\text{g}$ in CO_2e.

4.4 Disposing of the i-voting artefacts

The vast majority of the machines and equipment used for Internet voting are general-purpose computing devices that will not be destroyed after the elections but will be used for other applications.

The only things destroyed are one SSD storage device that is used for restoring the decryption key, the 9 chip cards that are used to store the shares of the private key, and about a dozen of DVD-s used to transport various data files between the computers during the processing of the votes.

We estimate the CO_2e emission of these disposals to be marginal, and emission per one of the 312181 i-votes being efficiently 0.

4.5 Summary of CO2e emissions for Internet voting

Table 4 gives an overview of CO_2e emissions for Internet voting. A discussion regarding the results is provided in Section 5.

Table 4. Summary of the CO_2e emissions for Internet voting

Parameter	CO_2e emission per vote (g)
Software development	0.35
Running the servers	11
Running the client applications	1.1
Disposing of the i-voting artefacts	0
Total:	≈ 12.5

5 Discussion

By comparing the values presented in Tables 3 and 4, we can see that the total CO_2e emission per vote is about 180 times higher in the case of paper voting. The main contributor to this difference is the emission occurring as the result of transporting the voters to the polling stations and back, followed by the emissions from running the polling stations.

However, we have to take into account that many of the parameters used in our assessments are approximate estimations which are inherently impossible to obtain precisely. Several values (carbon footprint of running the polling stations, the amount of transport required by the home voting) we had to estimate indirectly, and their margin of error may accordingly be higher. Also, our information was limited in regard to the ballot disposal methods applied in different districts.

Our study concentrated on the case study of Estonia, and hence several input parameters are specific to this country. For example, Estonia uses relatively small ballot sheets, which limits the amount of paper required. Also, in the 2023 parliamentary elections, vote casting via the Internet was used by more than half of Estonian voters. Accordingly, per-vote estimates similar to the ones in Table 4 would be larger in other jurisdictions where the amount of i-votes is smaller.

A significant role was probably played by the weather, which is still quite cold in Estonia in late February and early March. As a result, many voters may have opted for taking the car, and the need to supply energy to the polling stations had a remarkable footprint, too.

Our study does not cover the emissions caused by the activities necessary for both modes of voting. These activities include candidate registration, developing and running the elections information system, resolving disputes, etc. If we would also consider these emissions (say, adding half of them to both the estimated emissions of paper and Internet voting), the relative advantage of Internet voting in terms of CO_2e emission would be smaller.

6 Conclusions and further work

Voting is the core mechanism of implementing democratic decision processes in modern societies. As no significant alternatives to voting currently exist, one can not attach a price tag to it.

However, the existing technical solutions used for elections have evolved over the years and will probably continue to do so in the foreseeable future. Hence it does make sense to ask how to organise voting in a more optimal way, where different measures of optimality may be considered.

In this paper, we took the viewpoint of an ecologist and asked whether the introduction of new voting technologies (more specifically, vote casting via the Internet) has the potential to decrease the carbon footprint of elections. The answer is affirmative.

Even though preparing and running the voting software both on the servers and on the client side does contribute to CO_2e emission, nothing compares to the carbon footprint of the logistics of the voters to and from the polling stations. As parliamentary elections happen in late winter in Estonia, almost half of the paper voters chose to take the trip by car, which is one of the worst options from an environmental point of view. It would be interesting to calculate how much energy could be saved by moving the election date to a warmer period. However, at least in the case of Estonia, the date for parliamentary elections has been set in the constitution, so changing it is not really an option.

The second largest share of the carbon footprint can be attributed to running the polling stations (including heating and electricity supply). This was, however, the most challenging component to estimate, and the margin of error may be significant. Further research is needed to establish a reliable methodology for giving such estimates.

Another interesting future direction is determining the carbon footprint of other voting methods. For example, machine voting potentially has an even higher emission as the need to transport the voters to the polling stations is still there, but instead of (or in addition to) paper, one also needs to produce a large quantity of single-purpose devices, and this process carries a significant environmental footprint of its own. Postal voting from overseas is also a potentially interesting subject as there the environmental impact of ballot transport (e.g. by plane) would be significant.

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