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Published in:
Energy Reports

DOI:
10.1016/j.egyr.2024.01.024

Published: 01/06/2024

Document Version
Publisher's PDF, also known as Version of record

Energy Reports 11 (2024) 1517–1534

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Risks of climate change effects on renewable energy resources and the effects of their utilisation on the environment

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ARTICLE INFO

Keywords:
Renewable energy
Impacts on the environment
Climate change effects
Geothermal energy
Solar-based energy
Bioenergy

ABSTRACT

Renewable energy resources are essential for combating climate change. However, their use, production and collection have environmental impacts and climate change effects also affect them. The unique contributions were that the risks of climate change to renewable energy resources were addressed, which is addressed rarely before. Climate change, marked the increase of Greenhouse gases (GHGs), affects ground heat source, Asphalt/concrete-covered areas and borehole energy at about 0.5 risk levels. Toxicity emerges as the primary environmental impact from ground heat sources (0.7), asphalt/concrete-covered areas (0.6), borehole energy (0.9), and sediment heat energy production (1.6). Bioenergy sufficiency and cost affect bio-oil (2.25), biodiesel (1.9), bioethanol (2.4), biogas (2.3), forest biomass (2.3), and algae (2.3) at varying risk estimate levels. The most prevalent impact, observed across all bioenergy and biomass energy sources, is on biodiversity. Extreme weather phenomena impact ground wind energy (2.7), offshore wind energy (3.4), solar panels and collectors (1.3), and hydropower (1.2) at varying risk estimate levels. Ground and offshore wind energy have effects on birds and other animals at levels of about 1.3 and 1.1, respectively. Field-based biomass energy is affected by climate change more than other renewable energy resources. Ground heat sources were the least-affected type of renewable energy and the type with the fewest effects on the environment was solar energy/collectors. The significance of the study is that it helped to make it clear that renewables are safe for the environment. This study assists renewable energy sustainability by creating attractiveness and awareness of its risk-free facts to society. One of the novelties of the study is that new renewable energy sources were included – sediment heat, asphalt heat and water heat exchangers. The research concludes that even if the risks of renewable energy are much lower than fossil fuels, they are still significant and cannot be ignored.

1. Introduction

Risk can be defined as the possibility of the occurrence of a hazardous event that affects the achievement of objectives (Misra, 2008). Usually, risk causes negative impacts. Decision-making also is affected by the severity and characteristics of risk (Misra, 2008). According to Yaghlane et al. (Yaghlane et al., 2015), risk analyses have become much more important due to the increase in industrial accidents. However, this risk analysis article is not about industrial processes, but rather specific renewable energy resources that are affected by climate change, useful equipment for these resources and the risks of their utilisation to the environment. Risk can be environmental, economic, technological or social (Borghesi and Gaudenzi, 2013). In terms of environmental risk, the loss can consist of a naturally maintained environment becoming more polluted and insufficient for its ecosystems to survive. In economic terms, risk can include the loss of money. Technological risk can encompass loss of methods for producing products from the environment, such as energy available for collection or extraction falling dramatically due to a technology shortage. This is particularly relevant because technological advancements are essential for improving the efficiency and economics of renewable energy processes and for restricting CO_2 growth (Olabi and Ali Abdelkareem, 2022). Social risk,

Abbreviations: CHP, Combined heat and power; COVID-19, Coronavirus disease; GHG, Greenhouse gas; GHGs, Greenhouse gases; LCA, Life Cycle Assessment; PBR, Photobioreactor; PV, Photovoltaic cells.

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https://doi.org/10.1016/j.egyr.2024.01.024
Received 9 August 2023; Received in revised form 11 January 2024; Accepted 11 January 2024

on the other hand, includes the loss of an ideal living environment or social status. For example, climate change causes risks to our only living planet, which in turn implies risks for effective social survival. The future consequences of risk may be negative (hazard risks) or positive (opportunity risks) or could lead to uncertainty, and the lack (partial or total) of information (Borghesi and Gaudenzi, 2013). Climate change causes uncertainty for the whole world and its inhabitants.

According to (Misra, 2008), the steps in the risk management process are:

1. Identification of risk in a selected domain of interest;
2. Planning the remainder of the process;
3. Mapping out the social scope of risk management, the identity and objectives of stakeholders, and the basis upon which risks will be evaluated constraints;
4. Defining the framework that will be used in the activity and an agenda for identification;
5. Developing an analysis of risks involved in the process;
6. Mitigation of risks using available technological, human and organizational resources.

Fig. 1, which was originally presented in (ISO 0, 3100, 2015), shows a diagram that presents the solutions proposed in the risk management process.

Risk identification, risk estimation and risk evaluation are the most important steps in risk analysis. Risk identification is a distinct activity, which is a part of the risk assessment process (Borghesi and Gaudenzi, 2013). Furthermore, the full value of the risk identification procedure comes from its comprehensive description of the risks identified (Piney, 2003). The whole process of risk identification for this research was reported separately in the publication of Girgibo (Girgibo, 2022). Risk estimation and analysis were performed by creating two tables: 1. Climate change risks for renewable energy resources, and 2. Risks of renewable energy use and production to the environment. The experts consulted to estimate the risks were mainly from Finland, with the majority from the region of the city of Vaasa, with one from Sweden. They gave their estimations of risks on a scale from 0 (no risks) up to 6 (extremely high-level risks). After collecting these expert evaluations, the average values of all evaluations were calculated. Risk evaluation was carried out in two steps: 1. Eliciting expert opinions (Yaghlane et al., 2015): the research used quantitative methods based on expert opinions, meaning that experts were asked to quantify their judgments numerically. 2. The expert opinions are aggregated and averaged. The research appreciates the help of the experts who provided their opinions and assigned these opinions a risk level in the risk matrix.

Environmental risk can be defined as the potential or actual risks of various phenomena to the environment and living organisms. These effects can be due to emissions, resource depletion, effluents, wastes, et cetera. The ideas concerning the topic of technological risks brought up during the discussion with senior advisor were the following. The lack of a systematic means of integrating renewable energy globally is a primary problem in promoting the use of renewable energy technology and resources. Building infrastructure to buttress technology deployment was supported in policy proposals for an energy transition towards net zero emission resources (IEA, 2020). Environmental uncertainty and carelessness are the main risks associated with the use of renewable energy, in the sense of using environmental resources irresponsibly and eventually depleting them. The risk in Finland would be the end of forestry. The renewable energy market is new, which means there are not as many risks as fossil fuel energy resources, which are more developed. According to Wing and Jin (Wing and Jin, 2015), the sales price in the market is guaranteed by policies for renewable energy resources and grid access. New technology development leads to the obsolescence of older technology, which implies lower efficacy compared with newer versions (Gatzert and Kosub, 2016). Therefore, the early planning of projects using new technologies with renewable energy is risky, since equipment efficiency might develop further, leading into diminished public acceptance of the project and potentially less political support (Gatzert and Kosub, 2016). A major barrier to the use of renewable energy sources are national policies and policy instruments, which also affect costs and technological innovations (Owusu and Asumadu-Sarkodie, 2016). In addition, inaccuracy in early planning regarding resource assessment and the supply of renewable energy technology can also create risks (Gatzert and Kosub, 2016).

Risk matrices are a useful tool for risk assessment despite their limitations (Landell, 2016). Therefore, the risk matrix method was supported by other methods in this analysis. On the other hand, the risks of different renewable energy types have been addressed by some publications, including the following: Saner et al. (Saner et al., 2010) stated that the impact of ground source heat pumps in a life cycle analysis can be represented by CO_2 emission equivalence and that greenhouse gas (GHG) emissions are not the only impact of geothermal energy.

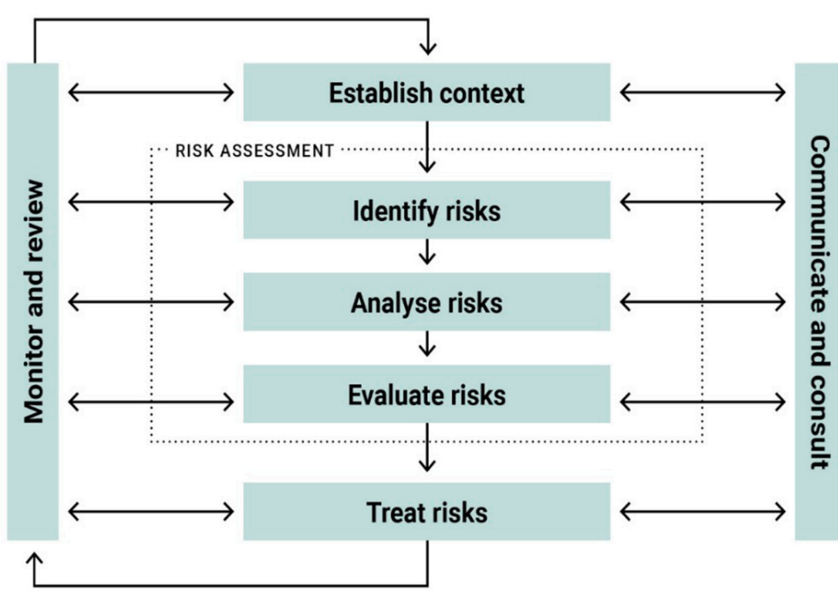

Fig. 1. A diagram presenting the solutions proposed for the risk management process. (The diagram was designed by Andrei Palomäki at Studio Andrei. The original source of the picture was (ISO 0, 3100, 2015)).

Greening (Greening and Azapagic, 2012) published a comprehensive analysis of different types of domestic heat pumps, covering their life cycle environmental impacts and the potential implications for the UK. Johnson (Johnson, 2011) showed that the footprint of heat pump refrigerants is a significant greenhouse gas pollution source. In 2012, a quarter of total energy consumption in Finland was due to wood fuel energy production (Energy and climate, 2014). This shows the importance of bioenergy in Finland. In addition, Energy and Climate (Energy and climate, 2014) state that the growth plan was for 25 TWh shares of Finnish electricity and heat production to come from forest chips by 2020.

According to Repo et al. (Repo et al., 2011), average emissions per unit bioenergy energy production from Norway spruce stumps decreased by about 20 % and bioenergy from branches decreased by about 60 % compared with the overall fuel cycle emissions of natural gas, after 50 years. 'The idea of biofuels production from micro algae is not new, but currently, it has received the keenest interests in an effort to combat global climate changes. Most of the studies have been focused on the following aspects: (1) the micro algae culture system, including raceway, photo bioreactor (PBR) and fermenter; (2) collection, screening and classification of micro algae, (3) molecular biology and genetic engineering; and (4) system analysis and resource assessment. The strengths of micro algae–based biofuels as the third-generation biofuels are many' (Zhu et al., 2014). Solar energy has the lowest impact on total greenhouse gas emissions relative to the national renewable energy targets of Finland (Sokka et al., 2016). The risks and environmental impacts of renewable resources cannot be ignored even if they appear to be small (Sokka et al., 2016). There are different types of renewable energy risks: environmental, economic, social and technological. Economic and social risks were not addressed in depth in this study. However, the environmental risks of renewable energy use and production were one of the key contributions in this paper. The number of researches who have addressed this issue is small. The other area of contribution was that of the risks of climate change to renewable energy resources. These are unique contributions that have not been addressed much in other studies, even compared with the environmental risks of renewable energy. The significance of the study is that aimed to help in making sure renewables are safe for the environment leading and helping renewable energy sustainability by creating attractiveness and awareness of its risk-free facts to society.

Novelty of this research compared with the current status on the investigated topics was done as follows based on former research publications. After reading of the 37 articles, most of them differed from the current article in the way that they focused on fossil fuels or non-renewables (In et al., (In et al., 2022); Moncada et al., (Moncada et al., 2018); Su et al., (Su et al., 2023); Zhong et al., (Zhong et al., 2023)), only on solar or wind energy (Costoya et al., (Costoya et al., 2019), (Costoya et al., 2022); Fant et al., (Fant et al., 2016); Kosmadakis et al., (Kosmadakis et al., 2021); Low & Honegger, (Low and Honegger, 2022); Mauleón & Hamoudi, (Mauleón and Hamoudi, 2017); Murphy et al., (Murphy et al., 2020); Schinko & Komendantova, (Schinko and Komendantova, 2016); Tariq et al., (Tariq et al., 2022); Zheng & Shahabi, (Zheng and Shahabi, 2023)), hydropower (Kumar et al., (Kumar et al., 2021); Zhao et al., (Zhao et al., 2023)), wave energy (Galparsoro et al., (Galparsoro et al., 2021); Ribeiro et al., (Ribeiro et al., 2021)), bioenergy (Pereira et al., (Pereira et al., 2015); Welfle & Röder, (Welfle and Röder, 2022)) or nuclear power (Bhattacharyya et al., (Bhattacharyya et al., 2022)). Many of them were also located in very different country compared to Finland, like China (Gong et al., (Gong et al., 2022); Lin et al., (Lin et al., 2022); Yang et al., (Yang et al., 2016)), Brazil (Dranka & Ferreira, (Dranka and Ferreira, 2018)), Russia and Ukraine (Lorente et al., (Lorente et al., 2023)), Iran (Shahnazi & Alimohammadlou, (Shahnazi and Alimohammadlou, 2022)), Malaysia (Ibrahim et al., (Ibrahim et al., 2022)), Australia (Goddard & Farrelly, (Goddard and Farrelly, 2018)) Africa (Sweerts et al., (Sweerts et al., 2019)) or comparison of many countries (Martí et al., (Martí et al., 2022)). Focus of articles were also different, like finance and prices (Polzin et al., (Polzin et al., 2019); Wang et al., (Wang et al., 2023); Xia et al., (Xia et al., 2019)), investments and willingness to pay (Hojnik et al., (Hojnik et al., 2021); Rahmani et al., (Rahmani et al., 2023)). Methodology of the former studies were different too, focusing on statistical methods (Kouloukoui et al., (Kouloukoui et al., 2019); Santos et al., (Santos et al., 2016)) instead of interviews, which were used in this research.

In addition, the novelty of this article is that the risk of climate change on renewable energy was not addressed in the previous scientific research and publication. The only environmental risk on renewable energy was the website (Concerned Scientists, 2013). Except that there has been significant publication how renewable energy is useful for combat climate change e.g (EEA report, 2018; Hannah, 2011). and IPCC reports, but not the risks of climate change to the renewable energy. In additions, the other novelty of this study is building on Holma et al. (Holma et al., 2018), the new renewable energy solutions which are the water heat exchanger, the sediment heat production energy system and the asphalt/concrete areas as a heat energy source, those were addressed in this article. This research addresses two gaps: Firstly, the absence of a scientifically based climate change risks analysis for renewable energy. To the authors knowledge there have not been any scientifically based climate change risks to renewable energy analysis. The previous publication Holma et al. (Holma et al., 2018) and Sokka et al. (Sokka et al., 2016) results in their analyses on the use and production of renewable energy risks to the environment have not include the new technologies, which are presented in this article. Secondly, existing risk analyses [61 and 19] lack coverage for newer technologies, specifically sediment heat energy and water heat exchanger.

The research questions addressed in this article are: 1. What and how much are the risks of climate change to renewable energy resources? 2. What and how much are the risks of renewable energy use and production to the environment?

2. Methods

The detailed procedures of this research were published in Girgibo (Girgibo, 2022). According to Misra (Misra, 2008), there usually are three main stages involved in quantitative risk assessment: risk identification; risk estimation; and risk evaluation. A similar procedure to that planned and used by Holma et al. (Holma et al., 2018), modified for this paper's expertise meetings, is described below. The method of expert view was chosen because of Holma et al. (Holma et al., 2018) indication that the process helps to assess risks in the field of renewable energy with professional person knowledge one can quickly identify the associated risks. This was true in this paper's case because the current research found similar results to that of Holma et al. (Holma et al., 2018) even though both used different expertise to analyse the environmental impacts of renewable energy use and production. Of the experts that provided evaluations, thirteen were from Finland and one from Sweden. These experts were divided roughly equally into three renewable energy resources groups: geothermal energy, bioenergy and biomass, and solar energy. More than 25 experts were contacted, but only 14 were able to deliver their evaluations. The overall data collection time was more than seven months since the first request was sent by email. The construction of the whole experiment and study took more than two years and began in March 2019. Similar evaluations were planned for both risks: 1) Risks to renewable energy resources caused by climate change and 2) risks to the environment caused by renewable energy production and use. Risk analysis was performed by experts, who evaluated the risks on a scale from 0 to 6, from 'no risk' to 'very high risk', as shown in the matrix of the risk analysis table. The scale is as follows: 6 = extremely high risk, 4 = high risk, 2 = medium risk, 1 = low risk and 0 = no risk; empty boxes were coded as zero risk (see Table 1 for similar explanations). All risks analysed in this study are negative risks or threats, not positive risks. However, the procedure consisted of the following steps:

Table 1
Risk estimate levels used in this study.

The risk analysis was carried out by who evaluated the risk level	Range used for this research in comparison with Holma et al. (Holma et al., 2018)	Definition of range in risk analysis in this research (and in Holma et al. (Holma et al., 2018))
6	Greater than 4.0 = Extremely significant	Extremely high risk (Extremely significant)
4	2.0 – 4.0 = Very significant	High risk (Very significant)
2	1.0 – 2.0 = Significant	Medium risk (Significant)
1	0.0 – 0.95 = Somewhat significant	Low risk (Somewhat significant)
0	0.0 = Not significant	No risk (Not significant)

1. Verbal discussions between the organiser group members and others on both types of risks and impacts.
2. Critical stage: determining the impacts and risks, with the overall impacts determined via verbal evaluations.
3. The group members identified both types of risks in identification tables.
4. The new risks identified were added to matrix tables for both risk identifications.
5. Panel discussion was not performed because of COVID-19 (Coronavirus disease). All members gave their rankings for the risk matrix tables through email.
6. All table data collected was calculated by the organisers.
7. After the calculation, the experts received the risk analysis result table by email.
8. The organisers requested comments on the final risk table.
9. Modification was carried out according to the comments.
10. The final table of risks will be sent to all experts by email. The result will be used in this article in risk analysis as the result and for further future analysis.

The panel discussion step could not be carried out due to the global coronavirus pandemic, which also affected the Vaasa region. Therefore, most face-to-face contacts were not used, but a few email discussions were conducted. Afterwards, the experts were asked to evaluate the risk analysis matrix and to send their assessments by email to avoid face-to-face contact. The result shows lower values, most between 0 and 1. This was because the result represents average risk level values for experts who replied for specific renewable energy types.

3. Results

3.1. Identification of risks

The whole risk identification process and results of this research were reported separately in the publication of Girgibo (Girgibo, 2022). The risks identified and used in the estimation had two classes: 1. Climate change risks and 2. Risks of renewable energy use and production to the environment. In the first category, the risks identified and used in the estimation matrix were extreme weather phenomena; wind speed; storms (wind speed and lightning); local or temporal air temperature increases; global warming; ice melting, including melting of ice in Greenland and polar areas and melting of permafrost in Siberia; increases in greenhouse gases (GHGs); precipitation increase; severe drought; sea level rise; water temperature increases; high waves; the thickness of ice in the sea and lakes, concretely the disappearance of sea ice; bioenergy sufficiency; the cost of bioenergy; the effects of land uplift; new plants in fields (invasive species); new insects in fields (invasive species); new trees in forests, with growing areas to the north and insects in the forest, including two generations in summer.

For the second (renewable energy risks to the environment) the research used similar risks (two new risks added in this research 'lowering of groundwater level' and 'effects on birds and other animals') to those that Holma et al. (Holma et al., 2018) identified: climate change, ozone depletion, acidification, tropospheric ozone formation, particulate matter formation: public health effects, eutrophication, toxicity, the impacts of biodiversity, soil depletion and soil quality, water use/water footprint, land use (land area as a resource), lowering of groundwater level (this groundwater risk identified was not included in Holma et al. (Holma et al., 2018)), abiotic resource depletion (metals, minerals, fossil fuels), radiation, plant pests and disease, and effects on birds and other animals. The easiest definition of toxicity is the quality of being very harmful or rapidly unpleasant. The similarity in these identifications helped us to compare this research results with those of Holma et al. (Holma et al., 2018), as presented in the discussion section of this article.

3.2. Estimation and analysis of risks

In the next subsections, the estimates for the risk levels of and to all types of renewable energy are presented. These results describe the average risk estimate levels based on expert opinions.

3.2.1. Geothermal energy risk analysis

3.2.1.1. Ground source heat. The risks of climate change to ground source heat were the lowest for all the geothermal energy types analysed here. The estimated risk level due to increased greenhouse gases was the highest, at about 0.5. The rest of the risk levels were below 0.5, with most being zero (see Fig. 2 for further information). Thus, one can conclude that ground source heat is the most promising among geothermal energy types since it will not be substantially affected by climate change effects.

The risks of the use and production of ground source heat mainly involved soil depletion and effects on soil quality, land use, and the groundwater level. The risk estimates for toxicity and soil depletion and soil quality were about 0.6 and 0.7, respectively. The risk estimates for land use and the groundwater level were 0.6 and 0.5, respectively. The remainder of the risk estimates were below 0.4, with some even being zero. Except for the risks of the use and production of shallow geothermal sources in terms of toxicity, land use, soil depletion and groundwater, the remainder of the risks are among the lowest compared with the other geothermal energy types analysed here (see Fig. 3 for a detailed understanding).

3.2.1.2. Asphalt/concrete-covered areas. The highest risks from climate change risks to renewable energy for asphalt/concrete-covered areas came from precipitation (rainfall) effects, with a risk level estimate of about 0.9. The increase in greenhouse gases had the second-highest estimate for asphalt areas, at about 0.5. Extreme weather phenomena, severe drought (lack of rain) and global warming were next, with roughly similar risk estimates of 0.4, 0.4 and 0.3, respectively. The rest of the risk level estimates were approximately zero, or at least below 0.2. The use of asphalt/concrete-covered areas for heat energy production seems to be the most promising strategy, in terms of climate change risks, aside from ground source heat (Fig. 2 for detailed results).

The use and production of asphalt/concrete-covered areas for heat energy production have some of the lowest risk level estimates. However, they have the highest estimated risk of producing toxicity, about 0.6. The mid-level risks, at around 0.3, were associated with climate change, particulate matter formation, public health effects, soil depletion and soil quality changes, land use and abiotic resources. The other risks generated by the use and production of asphalt energy were very low and indeed approximately zero (Fig. 3). This analysis shows that asphalt heat energy use and production was one of the safest technologies under consideration as an energy resource, in terms of its risks to the environment.

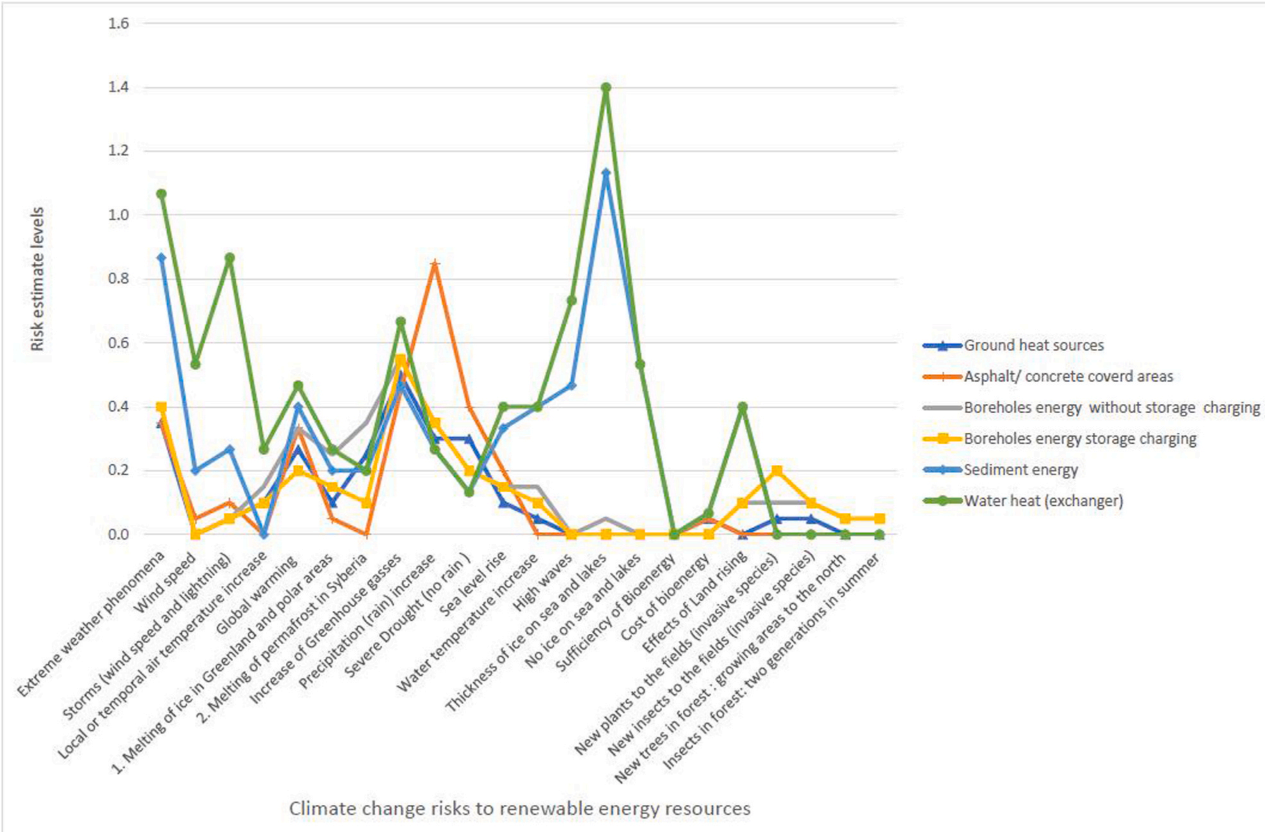

Fig. 2. Graph showing risk estimate level of climate change risks to geothermal energy types.

3.2.1.3. Borehole energy. Two types of geothermal borehole energy were analysed: boreholes with and without energy storage. The results are presented in the following sections:

3.2.1.3.1. Without energy storage. The climate change risks to geothermal boreholes without energy storage were found to be lower than the risks to geothermal boreholes with thermal energy charging. Among climate change risks, the highest were due to increased greenhouse gases for borehole energy without energy storage, with an estimated risk level of 0.5. Extreme weather phenomenon had a risk level of 0.4 for this energy type. Global warming, the melting of permafrost, increased precipitation and severe drought were estimated as having risk levels around 0.3, with the other risks being lower. In a general comparison between the two borehole types, boreholes with thermal energy charging were estimated to face more risks due to climate change.

Both borehole types have similar environmental use and production risks, based on this study's analysis. The main differences were in soil depletion and soil quality, and in toxicity. The borehole without energy storage charging was estimated to have a lower risk level for soil quality, soil depletion and toxicity levels. Soil depletion and soil quality risks were much lower for the borehole without energy storage charging (see Fig. 3 for detailed results).

3.2.1.3.2. With thermal energy charging. Among geothermal energy types, the borehole system with thermal energy charging has the third-highest risks due to climate change, while among the risks of climate change, increases in greenhouse gases represent one of the highest risks for the largest number of geothermal resources. In borehole energy with thermal energy charging, the increase of greenhouse gases is estimated to have a risk level of around 0.5. Estimated precipitation increases and extreme weather phenomena had a risk level of about 0.4. Global warming, new plants to the fields and severe drought were about 0.2. The risk levels for the melting of ice and sea level rise were about 0.15. The rest of the risk levels were estimated as below 0.1, with some risk levels even being as low as 0 (see Fig. 2 for detailed results).

The use and production of borehole energy with thermal energy charging represents a mid-level risk to the environment compared with the other geothermal energy types analysed here. The risk estimate for toxicity for the borehole system with storage charging was about 0.9. Lowering of the groundwater level was estimated to have a risk level of about 0.7. Public health effects and climate change were estimated at a risk level of about 0.5. The remainder of the risks caused by use and production of borehole systems with energy charging were below 0.5, which is low (see Fig. 3 for more detailed observations).

3.2.1.4. Sediment energy. Sediment energy was expected to face the second-highest climate change risks of all geothermal energy types, after the water heat exchanger, which faces the highest risks. The thickness of sea and lake ice has the highest risk, at about 1.1. Next, extreme weather phenomena are estimated to cause a risk level of about 0.9. The increase in greenhouse gases and high waves are estimated to cause risk in sediment energy at a level of about 0.5. Global warming is estimated to have a 0.4 risk level for sediment energy. Storms (wind speed and lightning) and severe drought (absence of rain) both were estimated at a risk level about 0.3. The rest of the climate change risk types were estimated to cause lower than a 0.3 risk level for sediment energy. Some risks associated with climate change even have a risk level of zero for sediment energy (Fig. 2).

Sediment energy use and production is estimated to have the highest risks to the environment (Fig. 3). Toxicity due to sediment energy has the highest risk level, about 1.6. Land use and abiotic resource depletion are estimated to be caused by sediment energy at a risk level of about 1.0. The risk level of public health effects was about 0.8. Climate change effects, effects on animals, lowered groundwater and particulate matter formation were estimated at about 0.7 or lower. The rest of the risks of

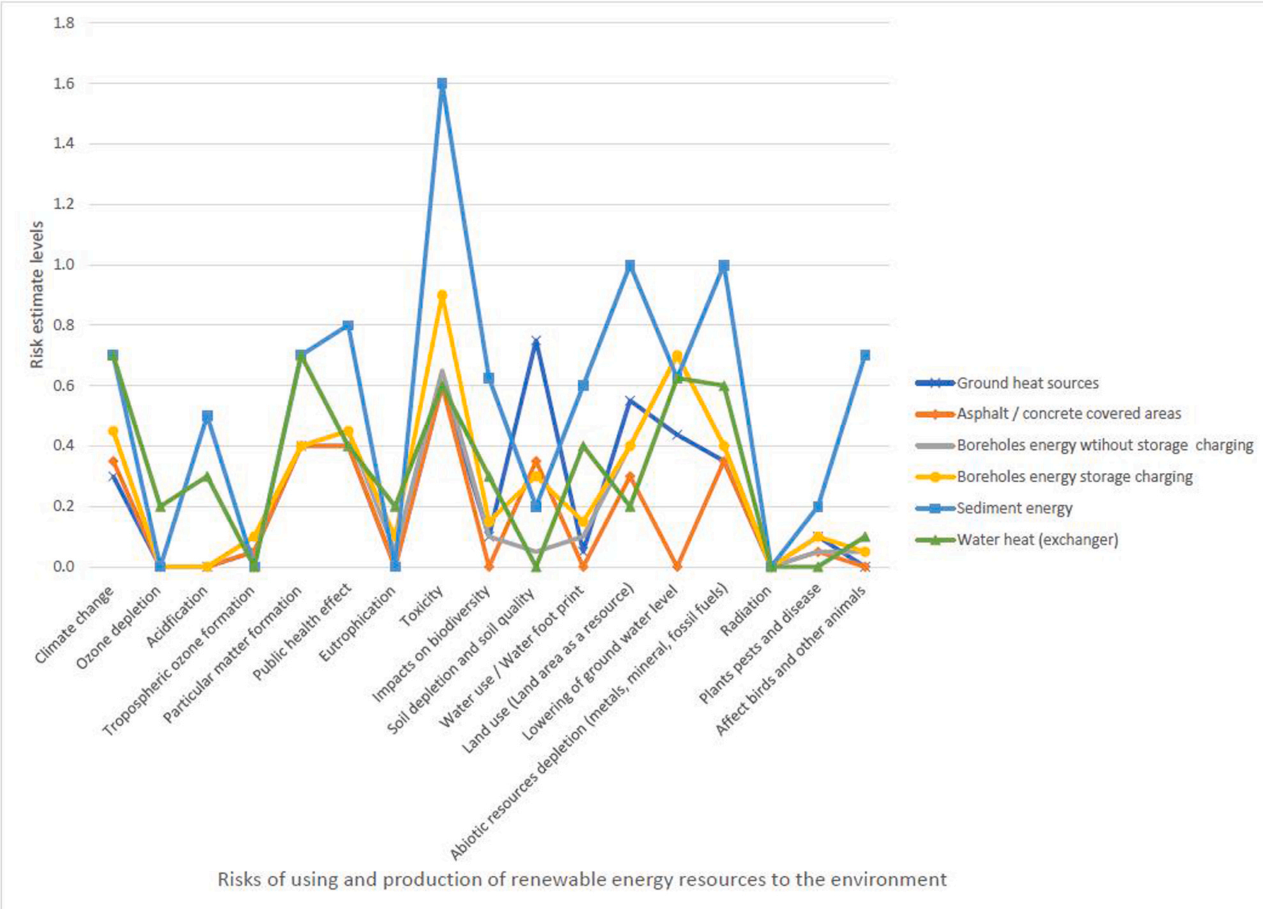

Fig. 3. Graph showing risk estimate level of the risks of the use and production of geothermal energy types to the environment.

sediment energy use and production to the environment are lower than 0.7. The risk levels of use and production of sediment energy to the environment are much higher compared with climate change risks to sediment energy. Similar patterns also were noticed in other renewable energy sources analysed here (Fig. 3). The production and use of renewables have low risks compared with non-renewable resources. Therefore, the benefits of renewable energy are much higher than its negative impacts, meaning that the use of renewables helps to safeguard the environment. However, the use and production of any type of energy has risks to the environment.

3.2.1.5. Water heat exchanger. The water heat exchanger has the highest risk due to climate change risks to renewable energy compared the rest of the geothermal energy types that were analysed in this study (Fig. 2). The risk estimated risk levels due to sea and lake ice thickness and extreme weather phenomena were 1.4 and 1.1. These were the highest compared to the other risks to geothermal energy analysed here. The other highest risks for the water heat exchanger are storms, high waves and increases in greenhouse gases, which had risk levels 0.9, 0.7 and 0.7 respectively. The lowest values observed for the water heat exchanger were related to bioenergy and forest risks among climate change risks. It was also noted that land uplift had possible risks around the 0.4 level. This means when the water heat exchanger installed, it must be installed in a deep site. Otherwise, if the heat exchanger is installed near the shore, after several decays the water level might not be high enough to generate sufficient heat. This is because land uplift can cause seawater levels to decline, particularly in shore areas and especially those in Scandinavia, such as the city of Vaasa, Finland (see Fig. 2 for further understanding of the results).

The water heat exchanger has some of the lowest renewable energy use and production risks to the environment compared with other geothermal energy types. The highest environmental risks of the water heat exchanger were climate change effects and particulate matter formation, which were both at a risk level of 0.7 (below 1) (Fig. 3). Please see the meaning of the risk level numbers in the methods section of this article (Table 1). The lowest values were zero (no risk) (Fig. 3). The rest of the environmental risks were between 0.7 and 0.0, which is below 1.0 (low risk). This makes the water heat exchanger one of the safest renewable energy technologies, since it presents little risk to the environment during its use and production stages.

3.2.2. Bioenergy and biomass risk analysis

3.2.2.1. Bio-oil. Bio-oil, biodiesel and bioethanol had very similar risks due to climate change effects. The bio-oil and biodiesel results are not visible because they are identical to the bioethanol plots (Fig. 4). The highest risk level for bio-oil was associated with climate change effect risks to bioenergy sufficiency and costs, with an estimated level of about 2.25. The next highest risk level for bio-oil was 2.0, for risks from extreme weather phenomena, severe drought, invasive plants and insect species. Wind, storm and global warming risks to bio-oil are estimated at about 1.4. The increase in greenhouse gas risks for bio-oil was about 1.25. The rest of the risks from climate change were below 0.8, which corresponds to precipitation. Some were even estimated as zero (Fig. 4). Climate change risks for bioenergy and biomass were the second highest among renewable energy types, after solar-based energies.

In terms of the risks of bio-oil use and production to the environment, their impact on biodiversity was the highest at 1.2. For almost all

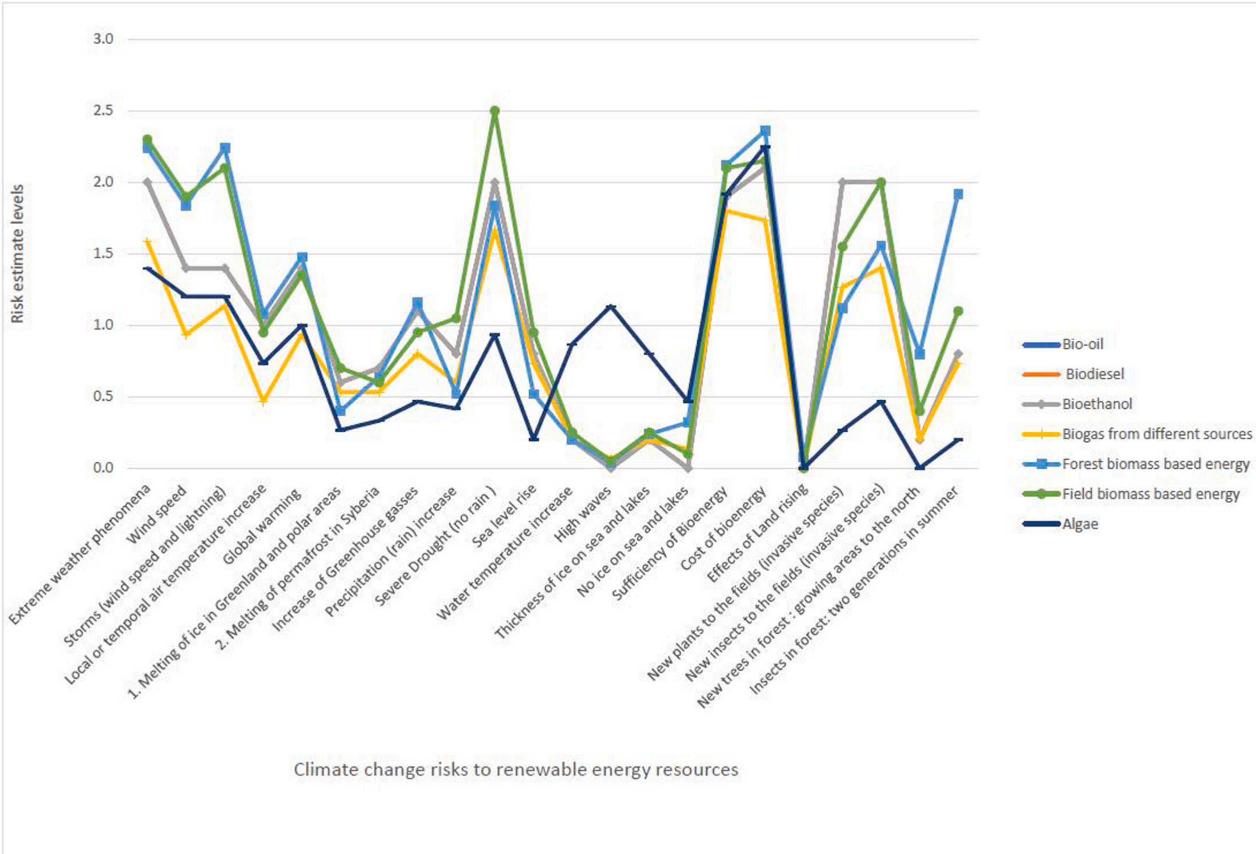

Fig. 4. This graph shows risk estimate levels for climate change risks to bioenergy and biomass energy types.

environmental risks of bioenergy and biomass use and production, the impact on biodiversity was the highest. The next highest risk level for bio-oil was 0.6, an estimate level that corresponded to plant pests and diseases, acidification and tropospheric ozone formation. Land use and its effects on birds and other animals were the next-highest risks of Bio-oil, at about 0.4 for both. The remainder of the risks are lower (see Fig. 5 for further details).

3.2.2.2. Biodiesel. Climate change risks to biodiesel are similar to those for bio-oil and bioethanol. The highest climate change risk for biodiesel corresponded to the cost of bioenergy, at a risk level about 2.25. The next-highest climate change risk level was about 2, corresponding to extreme weather phenomena, severe drought, bioenergy sufficiency, new plants in the fields and new insects in the fields. Wind speed, storms, and global warming also had a risk level of about 1.4 for the risks of climate change to biodiesel. Next came the effects of increased greenhouse gases, at about 1.25. The remainder of the risk estimate levels were lower than 1 (Fig. 4).

The risks of biodiesel use and production to the environment were also estimated. Biodiversity risks from use and production were found to be among the highest for most bioenergy and biomass. The impact of biodiversity was 1.5 for biodiesel. Toxicity due to biodiesel was estimated to have a risk level of 0.8. The next highest risk level was 0.6, corresponding to the risks of acidification, tropospheric ozone formation, particulate matter formation and plant pests and disease generated from biodiesel use and production. Ozone depletion, soil depletion and soil quality and effects on birds and other animals had a risk level of 0.4 for biodiesel. The rest of the risks were estimated as well below the 0.4 risk estimate level (Fig. 5).

3.2.2.3. Bioethanol. For climate change effect risks for bioenergy and biomass, the highest risks level for bioethanol corresponded to the cost of bioenergy, at about 2.25. The next-highest risk level estimate was about 2.0, corresponding to extreme weather phenomena, severe drought, new plants in the fields and new insects in the fields. The risks to bioethanol due to wind, storms and global warming were estimated at about 1.4. The risk level for bioethanol due to increases in greenhouse gases was about 1.25. The rest of the risks from climate change were below 0.8, which corresponded to precipitation and more insects in the forest. Moreover, some risks were estimated as zero (Fig. 4). It is important to note that bio-oil, biodiesel and bioethanol had the exact same risk level results for climate change effect risks.

Among the risks of the use and production of bioethanol to the environment, the highest risks came from its impact on biodiversity, at about 1.4. The risks of its effects on climate change were about 0.8. Acidification, tropospheric ozone formation and toxicity were the next highest risk levels, at about 0.6. The next-highest risk estimate level was 0.4. This estimate was for ozone depletion, soil depletion and soil quality, plant pests and disease, and effects on birds and other animals. The rest of the risk estimates were below 0.4 (Fig. 5).

3.2.2.4. Biogas from different sources. The highest risks to biogas due to climate change were associated with sufficiency of bioenergy, with a risk estimate level of 1.9. Severe drought had a risk estimate level of 1.8 and cost of bioenergy had a level of 1.7, which are among the highest risk estimate levels. Extreme weather phenomena and new invasive insect species in fields are expected to cause risk for biogas from different sources, with risk levels of about 1.6 and 1.4, respectively. New invasive plants in fields and storms are expected to cause risk levels of about 1.25 and 1.1, respectively. Wind speed was about a 0.9 risk estimate level, causing risks to biogas from different sources. The rest of the risk estimate levels are below 0.9 (Fig. 4).

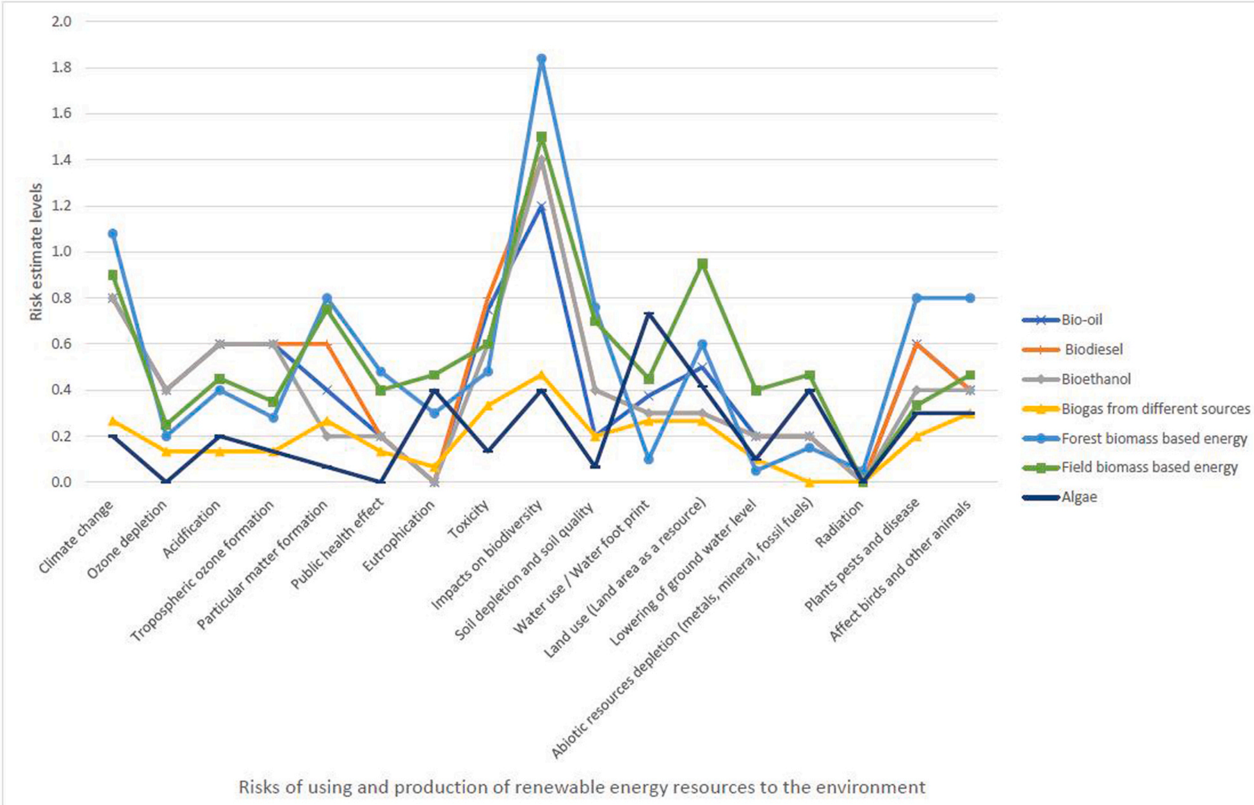

Fig. 5. This graph shows risk estimate levels of the use and production risks of bioenergy and biomass energy types to the environment.

The environmental risks of the use and production of biogas from different sources were also estimated by expert opinions. Biogas use and production had among the lowest risk levels compared to other bioenergy and biomass energy types. The highest risk caused by biogas was 0.5, for impacts on biodiversity. Toxicity and its effects on birds and other animals had a risk estimate level of about 0.3. The remaining risks to the environment from biogas were below 0.3, which is quite low (Fig. 5).

3.2.2.5. Forest biomass energy. The highest risks were associated with the costs of bioenergy, at a level of 2.4. This is a similar pattern to that seen for other types of bioenergy. Among the climate change risks to forest biomass energy, storms and extreme weather phenomena both had a risk estimate level of about 2.2, which is one of the highest. Severe drought and more insects in the forest with two generations per year had risk estimate levels of almost 2.0. Global warming and new invasive insect species in fields had risk estimate levels of almost 1.5. Increased greenhouse gases and new invasive plants in fields had risk estimate levels of almost 1.2. New trees in the forest with growing areas had a level of 0.8. The rest of the risks caused by climate change effects were at or below the 0.5 risk estimate level (Fig. 4).

The use and production of forest biomass energy causes environmental risk as well, and indeed these risk levels were among the highest among bioenergy and biomass energy types. The highest risk estimate for forest biomass energy is 1.8 for impact on biodiversity. Effects on climate change had a risk level of about 1.1. A risk level of around 0.8 was associated with particulate matter formation, plant pests and diseases, and effects on birds and other animals. Land use (land area as a resource) impacts were caused by forest biomass energy use and production with a risk estimate level of 0.6. Toxicity and public health effect risk impacts caused by forest biomass energy were estimated to be around 0.5. The risk level of acidification was around 0.5 as well. Tropospheric ozone formation and eutrophication risks were about 0.3. The risks levels of ozone depletion and abiotic resource depletion (metals et cetera) were around 0.2. The rest of the risks caused by forest biomass energy use and production were about or below 0.2 risk estimate levels. Better observation and comparisons can be seen in (Fig. 5).

3.2.2.6. Field biomass energy. Field biomass energy faced risks due to climate change effects. Some risks of climate change to field biomass energy were estimated in this study as well. Severe drought (absence of rain) was the highest risk, estimated at a risk level of around 2.5. Extreme weather phenomena and the cost of bioenergy were both estimated to have a risk level of about 2.3. Storms and sufficiency of bioenergy had a risk estimate level of about 2.1. New invasive insect species in fields caused an estimated risk level of 2.0 for field biomass energy. Wind speed risk was 1.9 and new invasive plants species risk was 1.6. On other hand, global warming was estimated to cause a risk level of 1.4. Insects in the forest (two generations per summer) and precipitation were estimated to have a risk level of 1.1. The local or temporal temperature increase, the increases in greenhouse gas emissions and sea level rise have an estimated risk level of about 1.0. The melting of ice in Greenland and polar areas and the melting of permafrost in Siberia had risk estimate levels of about 0.7 and 0.6, respectively. Growing areas of new trees in the forest in the north had a risk estimate level of about 0.4. Risks due to water temperature and the thickness of ice in the sea and lakes were about 0.3. The rest of the risks caused by climate change effects were below 0.3 and some were even close to 0 (Fig. 4).

The use and production of field biomass energy affects the environment. Effects on biodiversity represented the greatest risk of field biomass energy, at about 1.5. Risks to land use (land area as a resource) and climate change were next, at a risk level of about 1.0 and 0.9, respectively. Particulate matter formation and soil depletion and soil quality due to field biomass energy had risk estimate levels of about 0.8 and 0.7. Toxicity had a risk estimate level was about 0.6. Acidification, eutrophication, water use/water footprint, abiotic resource depletion (metal, minerals, fossil fuel and so forth) and effects on birds and other animals were all at a risk estimate level of about 0.5. Tropospheric ozone formation, public health effects, and lowering groundwater levels were around the 0.4 risk estimate level. Ozone depletion and plant pests and diseases were risks at a level of about 0.3. The lowest risk was radiation risk, which has a 0.0 risk estimate level caused by field biomass energy use and production (Fig. 5).

3.2.2.7. Algae. For risks to algae because of climate change effects, the cost of bioenergy and sufficiency of bioenergy had risk levels of about 2.3 and 1.9, respectively. Extreme weather phenomena had a risk level to algae of approximately 1.4. Wind speed and storms had a risk estimate level of about 1.2. High waves had a level of about 1.1. Global warming risk was 1.0, severe drought was 0.9, water temperature was 0.9, the thickness of ice in the sea and lakes was 0.8 and local or temporal air temperature was about 0.7. The risk levels due to an increase in greenhouse gases and new invasive insect species in fields were 0.5. The risk levels due to increased precipitation were 0.4, the risk due to melting of permafrost were 0.3, and the risk due to new invasive plant species in the fields was around 0.3 (Fig. 4). It was also noted that algae were the least affected by climate change effects among bioenergy and biomass energy types.

Water use/water footprint had the highest risks due to the use and production of energy from algae, at a risk estimate level of about 0.7. Risks at about a 0.4 risk estimate level included eutrophication, impacts on biodiversity and abiotic resources depletion (metals, minerals, fossil fuels et cetera). The risk estimate levels of plant pests and disease and effects on birds and other animals were around 0.3. Acidification and climate change had risk estimate levels of around 0.2. Risks due to toxicity, soil depletion and soil quality, and lowering groundwater levels were estimated at about 0.1. Risks from ozone depletion, public health effects and radiation were all estimated at 0.0.

This concludes the risk analysis of climate change effects on bioenergy and biomass, as well as bioenergy and biomass energy use and production risks to the environment. In the following two figures (Fig. 4 and Fig. 5) there is more information about the risks of bioenergy and biomass.

3.2.3. Solar energy-based risk analysis

3.2.3.1. Wind energy. There are two types of wind energy to be analysed, ground and offshore wind energy. Both are covered in the following sections.

3.2.3.1.1. Ground. Ground wind energy was mainly affected by a few climate change risks: extreme weather phenomena, wind speed and storms with estimated risk levels of 2.7, 2.5 and 2.6, respectively. In these risk types, the estimated risk levels were the second highest among solar based energy types, after offshore wind energy. Local or temporal air temperature risks affected ground wind energy about at a 0.7 risk estimate level, which quite low compared with the previously mentioned risks. Severe drought had a risk estimate level of about 0.6. Further, the rest of the risks generated by climate change effects on ground wind energy are below the 0.5 risk estimate level. Fig. 6 presents the rest of the results for risks generated by climate change effects.

Land use (land areas as a resource) represented the highest risks of ground wind energy to the environment at a risk estimate level of about 1.8. Impacts on biodiversity and effects on birds and other animals had risks of about 1.1 and 1.3, respectively. Impacts of ground wind energy on abiotic resource depletion and climate change were around 0.9 and 0.8, respectively. Particulate matter formation and public health effects both had risk estimate levels of around 0.5. Soil depletion/soil quality and water use/water footprint risks were both around 0.2. The rest of the environmental impacts of ground wind energy had zero estimated risk (Fig. 7).

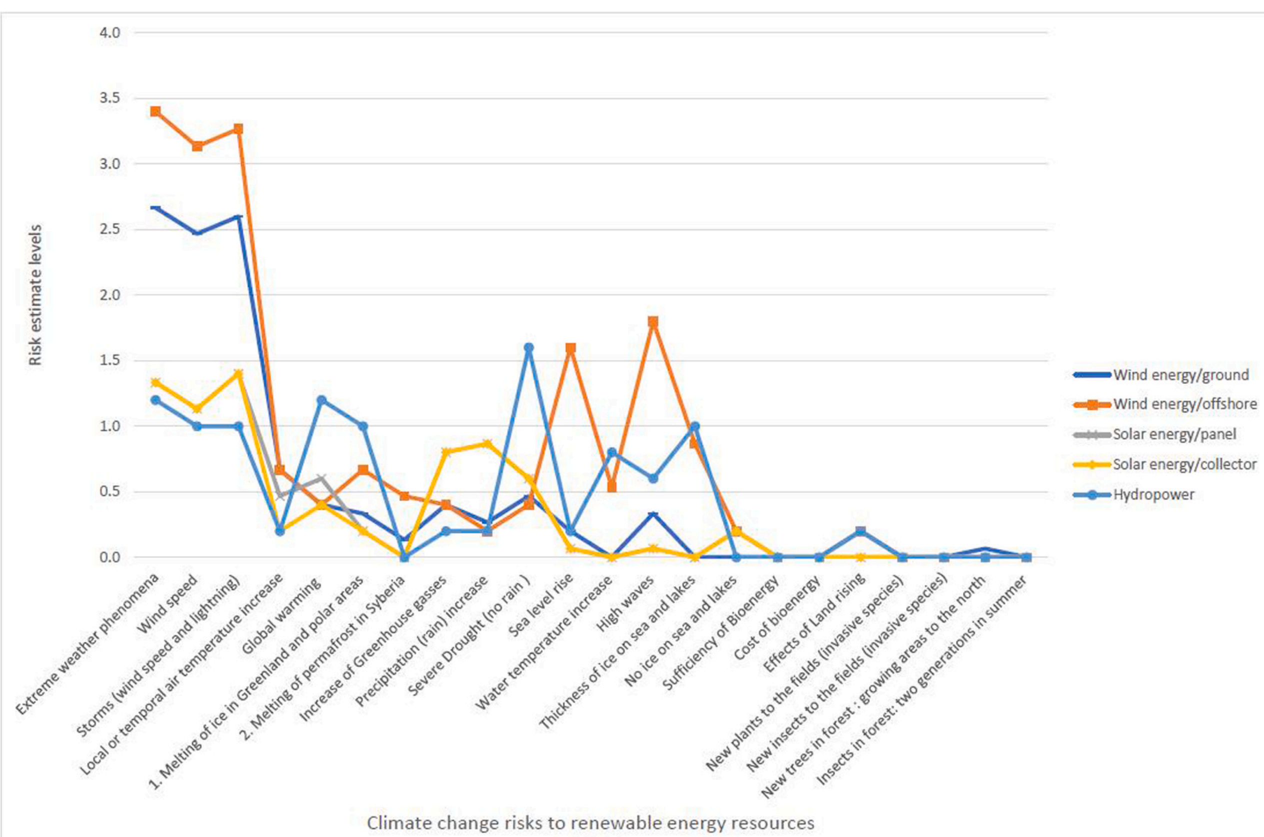

Fig. 6. Graph showing risk estimate levels of climate change risks to solar-based energy types.

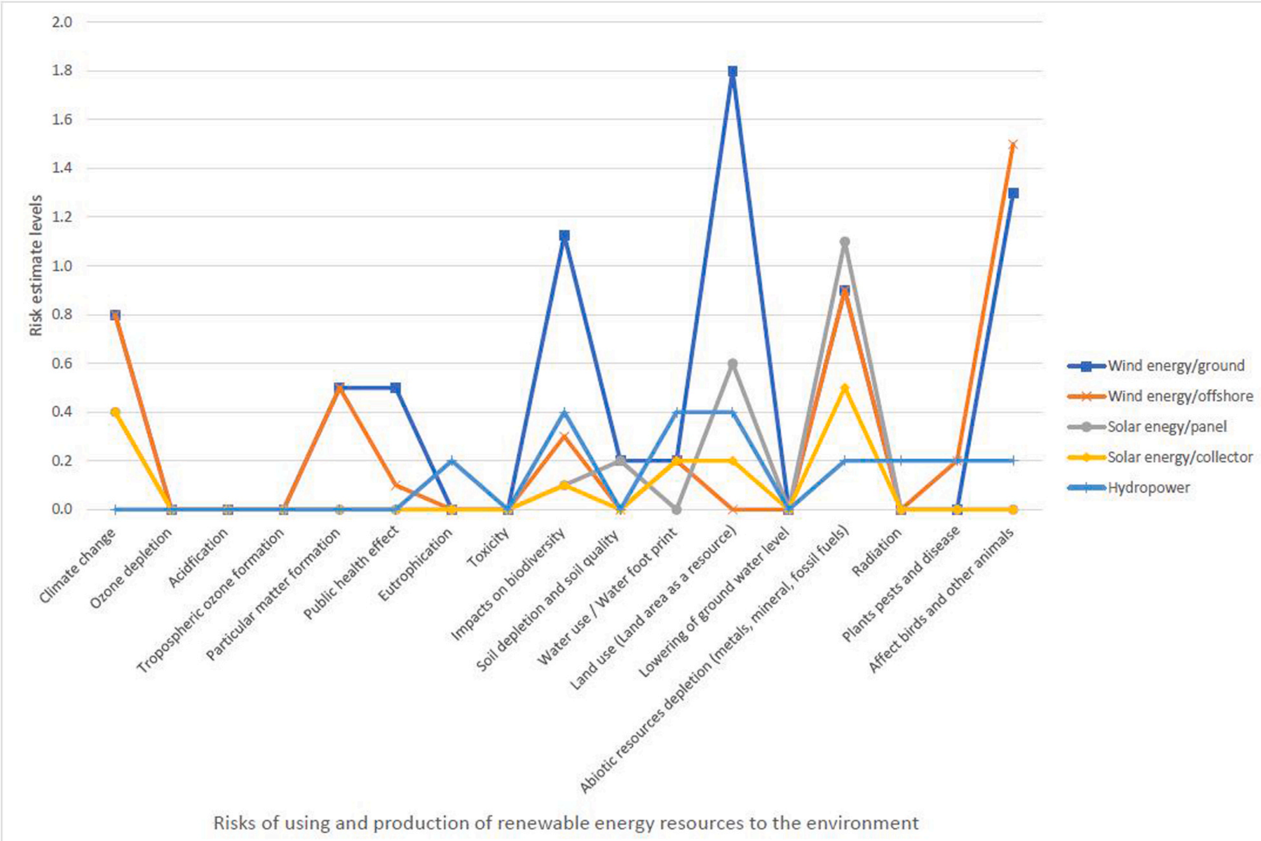

Fig. 7. Graph showing risk estimate levels of the use and production risks of solar-based energy types to the environment.

3.2.3.1.2. Offshore. The highest risks for offshore wind energy were extreme weather phenomena, wind speed and storms, which have risk estimate levels of 3.4, 3.1 and 3.3, respectively. The other high-risk estimates were only for sea level rise and high waves, at levels of 1.6 and 1.8. This is expected because offshore wind energy is mainly installed in open waters. Therefore, any water-related risks also affect this energy source. The next-highest risks are the thickness of ice on the sea and lakes, local or temporal air temperature increases, the melting of ice in Greenland and polar areas, and sea and lake ice thickness, which all had risk estimate levels of about 0.9 or below. The melting of permafrost in Siberia, severe drought, and water temperature increases were about 0.5. Further, the rest of the risks created by the effects of climate change were below 0.5 (see Fig. 6 for further information).

There are five main environmental risks of the use and production of offshore wind: effects on birds and other animals, abiotic resource depletion, climate change, impacts on biodiversity and particulate matter formation, which have risk estimate levels of 1.5, 1.1, 0.8, 0.3 and 0.5, respectively. These analyses are important because they clearly show the variation between ground (onshore) and offshore wind energy risks. Similar comparisons can be carried out across all renewable energy analyses. The rest of risks generated by offshore wind energy were at or below the 0.3 risk estimate level. See Fig. 7 for further observations.

3.2.3.2. Solar energy. There are two means of using solar energy: solar panel → electricity and collector → heat. The results for both are given in the following sections. These panels and collector types have relatively similar risks and they have similar climate change effects, with only a few differences.

3.2.3.2.1. Panel. Among the risks of climate change effects to solar panel energy, the highest risk was estimated for storms, at a risk estimate level of about 1.4. The next-highest risk is due to extreme weather phenomena, at a risk estimate level of about 1.3. Wind speed had a risk estimate level of about 1.1. Increased precipitation and increased greenhouse gases were at the 0.9 and 0.8 risk estimate levels, respectively. Severe drought (absence of rain) and global warming were around the 0.6 risk estimate level. Local or temporal air temperature was around the 0.5 risk estimate level. The rest of the climate change risks to panel solar energy were below 0.5. For more information, see Fig. 6.

Solar-based energy types have similar patterns in their use and production risks to the environment. This is true for panel solar energy as well. Among the risks of solar panel energy, abiotic resource depletion has a roughly 1.1 risk estimate level, which is the highest value for the risks of solar panel energy. Land use (land areas as a resource) had risk estimate levels about 0.6. Climate change had risks from solar panel energy of about 0.4. Impacts on biodiversity and soil depletion and soil quality had risk estimate levels of 0.1 and 0.2, respectively. The rest of the risk estimate levels are at or below 0.1, with most being zero. The rest of the results are presented in Fig. 7.

3.2.3.2.2. Collector. The highest risks of climate change effects on solar energy collector technology were due to storms (wind speed and lightning). The risk estimate level was found to be 1.4 based on the average of the expert opinions. Extreme weather phenomena and wind speed were the next-highest risks for collector solar energy, at about 1.3 and 1.1, respectively. The other risks that were visible for solar collectors were due to precipitation, increased greenhouse gases and severe drought, at risk levels of about 0.9, 0.8 and 0.6, respectively. Global warming had a risk estimate level of about 0.4. Local or temporal air temperature was around a 0.2 risk estimate level. The rest of the climate change effect risks were below 0.2 (Fig. 6).

The use and production of collector solar energy has risks. Abiotic resource depletion is the highest risk generated by collector solar energy, at a risk estimate level of about 0.5. Effects on climate change, water use/water footprint effects and land use (land area as a resource) were at risk estimate levels of about 0.4, 0.2 and 0.2, respectively. The rest of the results show that all the other types of risks due to collector solar energy were below 0.2 and most risk estimates generated were zero. For further observations, see Fig. 7.

3.2.4. Hydropower

Hydropower was found to be one of the solar-based energy resources least affected by climate change effects. Among climate change effects, drought is the highest risk for hydropower, at a risk estimate level of about 1.6. Extreme weather phenomena and global warming were found out have risk estimate levels of about 1.2. Wind speed, storms, melting of ice in Greenland and polar areas, and sea and lake ice thickness all were found out to have similar risk levels, about 1.0. Water temperature increases and heat waves had risk estimate levels of about 0.8 and 0.6. The local temporal air temperature increase, the increase in greenhouse gases, precipitation, sea level rise and the effects of land uplift all affect hydropower at the same level, about 0.2. The rest of the climate change risks included in this analysis were found to have a risk estimate level of 0.0 (the results are presented in full in Fig. 6).

Among solar-based energy resources, the use and production of hydropower was one of those that least affected the environment, after solar/collector energy production, based on a comparison of the total sum of the average risk values. The highest risks due to hydropower were determined to be impacts on biodiversity, water use/water footprint, and land use, all with risk estimate levels at about 0.4. Eutrophication, abiotic resource depletion (such as metals), radiation, plant pests and diseases, and effects on birds and other animals were all at about the 0.2 risk estimate level. The rest of the risks of hydropower were zero. For further observations, see Fig. 7.

3.3. Evaluations of the risks

Table 2 presents the summarised evaluations and a comparison between the risk analysis results for the different renewable energy types. In addition, it presents the least and most affected or affecting renewable energy types for the two risk analyses conducted in this research study. Regarding the risks of climate change effects on all renewable energy resources, the least affected was ground heat source energy and the most affected was field biomass energy. These evaluation decisions were made based on the generalisation of the result described above and by comparing with the total average summed risk values, as well as comparing and checking within each renewable energy resource types. In evaluating climate change effect risks to geothermal energy resources, the least affected sources were ground heat sources and the most affected were water heat exchangers. Regarding climate change effect risks to bioenergy and biomass energy resources, the least affected were algae resources and the most affected was field biomass energy. Regarding the risks of climate change to solar based energy resources, the least affected were solar energy/collectors and the most affected was wind energy/offshore.

Table 2
Generalising the renewable energy resources with the best and the worst average risk levels (also checked by the average risk estimate total sum for each energy resource).

Renewable energy resources	Risks of climate change effects to the renewable energy		Use and production of energy resources risks to the environment	
	Least affected	Most affected	Least affecting	Most affecting
Geothermal energy resources	Ground heat source	Water heat exchanger	Asphalt/ concrete covered areas as heat sources	Sediment heat energy
Bioenergy and biomass energy resources	Algae	Field biomass energy	Biogas from different sources	Field biomass energy
Solar-based energy resources	Solar energy/ collector	Wind energy/ offshore	Solar energy/ collector	Wind energy/ ground
Comparing all energy resources	*Ground heat source*	*Field biomass energy*	*Solar energy/ collector*	*Field biomass energy*

Among the environmental risks due to the use and production of renewable energy resources, the least risky were solar energy/collectors and the riskiest was field biomass energy. Field biomass energy was determined to be the riskiest to the environment among all renewable energy resources, as well having the highest risk due to climate change effects. For geothermal energy resources, the least risky was energy using asphalt/concrete covered areas as a heat source and the riskiest were sediment heat energy resources. Among bioenergy and biomass energy resources, biogas from different sources had the least effects and field biomass energy resources had the most. For solar-based energy resources, the one with the least effects was solar energy/collectors and one with the most effects was ground wind energy. The best energy resources, those that had the fewest environmental effects and were the least affected by climate change effects, were solar energy/collectors and ground heat sources, respectively.

Based on the overall evaluation, Figs. 8 and 9 were created based on the total average risk estimate values. As stated in Table 2, among the climate change effect risks on renewable energy, the most affected is field biomass energy and the least affected is ground heat source energy. See Fig. 8.

As stated in Table 2, among the use and production risks of renewable energy resources, the resource with the greatest effects was field biomass energy and the resource with the lowest effects was solar energy/collectors (Fig. 9).

The following paragraphs present the arguments relative to the validation of the risk analysis process. Risk analysis was performed with a procedure similar to that of Holma et al. (Holma et al., 2018), namely risk analysis based on data collection through expert evaluations (see for detailed procedures and steps (Girgibo, 2022)) This method is a well-recognised method in risk analysis. The experts were chosen such that they have in-depth knowledge of at least one of the renewable energy technology types. Having a group of experts for data collection helps gather the best risk information for all types of renewable energy. Therefore, the experts' views measure the existence and magnitude of the risks. The only limitation was that the number of experts was low (14 experts out of 25 who were asked for their risk evaluation), but this number nonetheless is comparable with that of Holma et al. (Holma et al., 2018), who used 20 experts. This means that this research results can indicate the direction for risks and can serve as a starting point for future in-depth investigation into the risks of renewable energy. The method used in this risk analysis also was used by (Holma et al., 2018). This method is sufficiently accurate to collect good data on risks and on renewable energy. The experts chosen were knowledgeable about their own specific renewable energy types. It was noted that they could perceive and understand the different types of risks in the renewable energy resource types. The generalisability of the method is such that at least its national-level accuracy was sufficient.

The risk analysis and management concept are suitable for assessing the risks of renewable energy. Its repeatability and reproducibility can be guaranteed if the right types of experts are present. The opinion of one expert might differ from that of another. However, the average results certainly can show similar patterns. The repeatability of the concept in different locations is quite feasible, though it probably will produce different results because of the area specificity of specific renewable energy sources and of their production methods. Different risks to renewable energy due to climate change can be present in different places. Risk analysis of renewable energy resources was mainly built upon a mixed qualitative and quantitative strategy. It is more qualitative, and thus a lack of identification of statistical analysis uncertainties seems certain. Therefore, more uncertainties can be identified by the Type-B error method instead of the Type-A error method. The

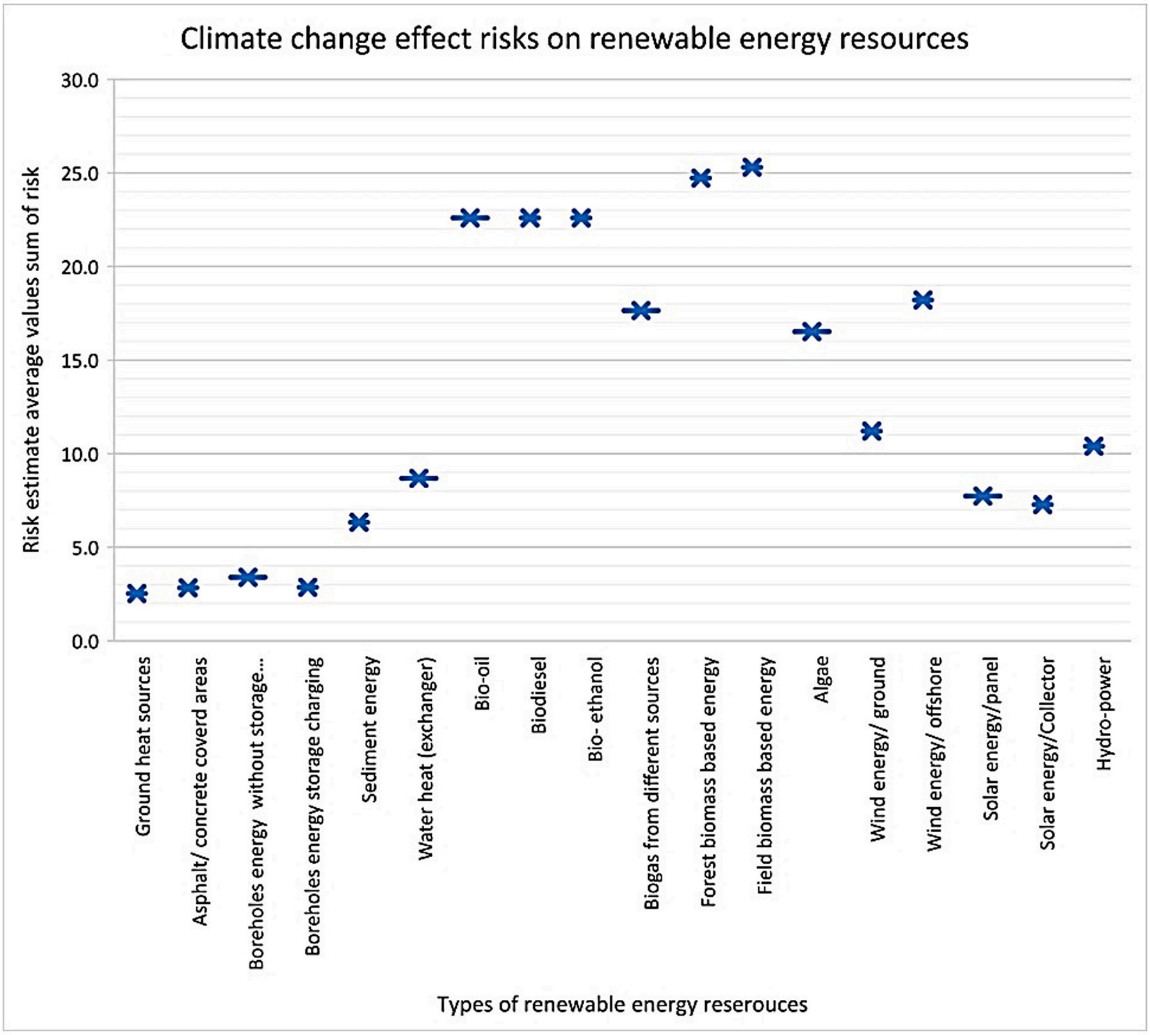

Fig. 8. Graph showing the sum of the average risk estimate levels of climate change risks to all renewable energy resources.

uncertainties of the risk analysis of renewable energy resources can be identified through the Type-B error method. This concept of risk analysis of renewable energy has uncertainties that can might be generated by the small number of respondents. Thus, it may be difficult to accurately generalise the concepts to a global scale. However, as previously stated, before this concept the analysis was planned to be a starting point for larger risk analysis investigations.

The researchers are aware of the small number of expert respondents for this risk analysis. In addition, the generalised averaged risk estimate levels might be different with larger numbers of expert respondents. The main uncertainties that can be present in risk analysis of renewable energy resources are due to the small number of experts. This is one of the uncertainties that can be identified by the Type-B error method. The researchers attempted to mitigate this problem by comparing this research findings with the publication of Holma et al. (Holma et al., 2018) on risks of the use and production of renewable energy to the environment. The results are similar in most cases. However, climate change effect risks to renewable energy cannot be compared with Holma et al. (Holma et al., 2018), because they did not study this aspect of risk. The analysis of climate change risks is a new result. Thus, the uncertainties generated by the small number of experts responding to the risk analysis are still present. Both aspects of risk were planned to serve as a starting point for future in-depth analysis of risks to and from renewable energy resources.

4. Discussions

Identifications of risk types in renewable energy were carried out by examining different resources for risk types according to Holma et al. (Holma et al., 2018), In addition, some experts who participated in this risk analysis also contributed to the risk identification process. The risks identified and used were presented in the results section and in publication of Girgibo (Girgibo, 2022). Two risks, which were identified in addition to those from Holma et al. (Holma et al., 2018), fell under the category of risks to the environment due to the use and production of renewable energy: lowering groundwater and affecting birds and other animals. The risks of climate change effects on renewable energy were all new and not considered in (Holma et al., 2018). Those identifications also can be found in the results section. The climate change effects were presented in depth in all IPCC reports (e.g (IPCC, 2013). and (IPCC, 2021)). It was believed that all possible risk aspects were addressed to obtain the most possible results.

The estimation and analysis results were presented for all renewable energy types analysed in this research. The first section covered geothermal energy types, including ground heat sources, asphalt/ concrete-covered areas, borehole energy (without energy storage and with energy storage charging), sediment energy and water heat exchangers. Among these, the least affected by climate change was ground heat source energy, because it is located underneath the surface of the Earth. Thus, the change due to weather patterns and global warming is

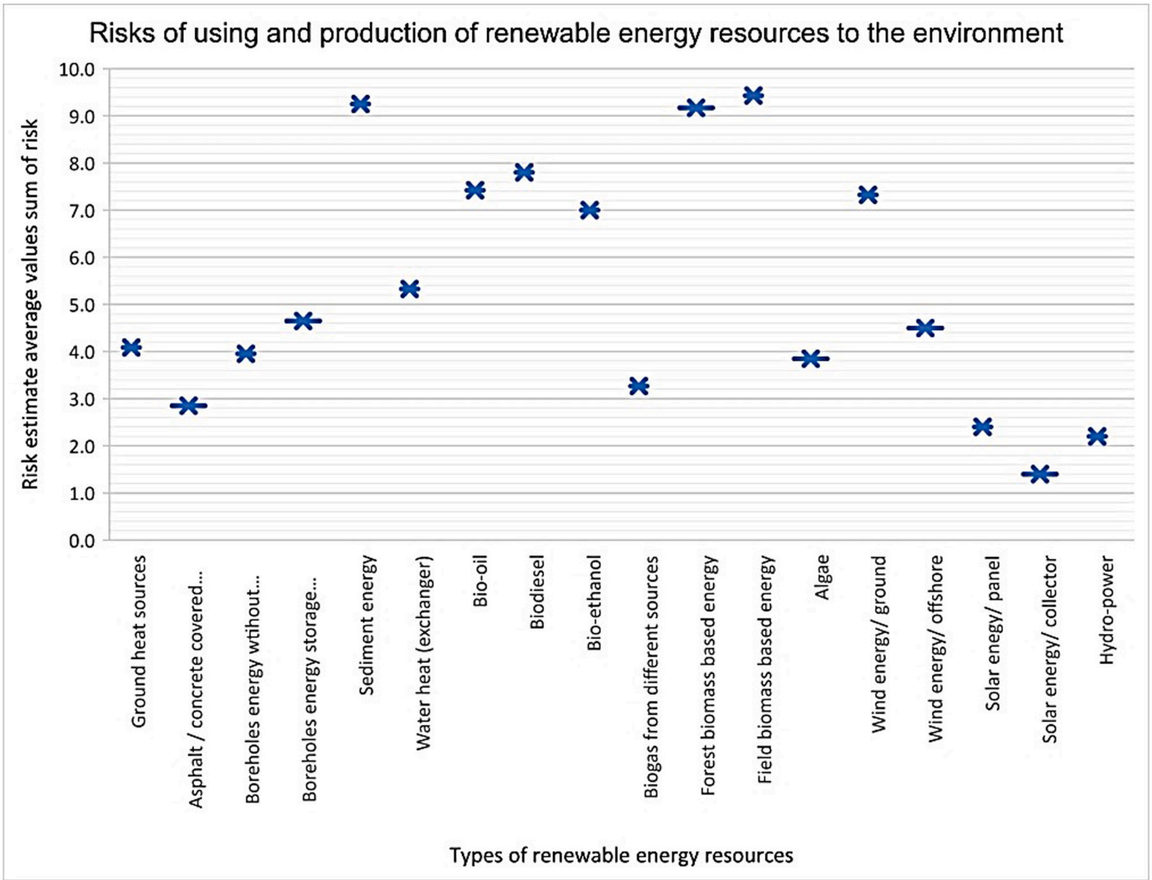

Fig. 9. Graph showing the sum of average risk estimates level for the environmental use and production risks of all renewable energy resources.

very limited. The most affected by climate change are water heat exchangers. This is because the water heat exchangers are installed underwater, and both the water and the exchanger have been affected severely by changes in air temperature and solar irradiance. These evaluations were carried out based on the average total results. Among the risks due to the use and production of renewable energy resource, the riskiest was sediment heat energy. On other hand, it has been found that sediment heat energy uses climate change effects to its advantage, at least in summer (Girgibo et al., 2022). However, the average total result shows that sediment heat production has the largest effects among geothermal energy resources.

The use of asphalt/concrete-covered areas as the heat source was found to have the least effects on the environment. This is because this energy is built under asphalt or concrete layers and even in pre-existing structures. The University of Vaasa has been very active in both sediment heat energy and the use of asphalt/concrete areas as heat sources. Both are new renewable energy technologies. This finding on how they affect the environment helps in planning their implementation and management. Ground heat source energy was also found to have the least effects across all types of renewable energy resources. Thus, this was the best renewable energy technology, since it was also among the least affected. Bioenergy and biomass energy were the other type of energy that was analysed for their risks. Among all types of bioenergy and biomass, field biomass was found to be the most affected by climate change effects and to have the most effects on the environment. Thus, this is one of the riskiest types across all types of renewable energy. The source least affected by climate change was algae and the source with the fewest effects on the environment was biogas from different sources. Climate change effects least affected solar energy/collectors, which also had the lowest environmental effects. This makes it the best technology among solar-based energy resources. However, according to Solaun et al. (Solaun and Cerdá, 2019), literature on the climate change impacts of solar sources has received less attention than that on wind or hydropower. Across all renewable energy, the least affecting to the environment was solar energy/collectors. The source that was most affected by climate change effects among solar-based energy resources was offshore wind energy. Ground wind energy was found to have the most effects on the environment among solar-based energy resources. Cronin et al. (Cronin et al., 2018) have critically reviewed the literature on the impacts of climate change on the energy supply system, summarising the regional coverage of studies, trends in the results and sources of disagreement. In their study, they noted that several authors had commented that the negative impacts of climate change on wind and solar generation and infrastructure will be insignificant since the rapid development and relatively short lifetimes of these technologies allow adaptation through technological upgrades and siting.

Comparing this research result with those of Holma et al. (Holma et al., 2018) shows the similarity of the risk estimates in most cases for the risks of the use and production of renewable energy to the environment. However, this does not hold for some risks, mainly in solar energy and hydropower technologies. See Table 3 in the appendix section of this article for these comparisons. The other part of the risk analysis, which consists of climate change effect risks to renewable energy, is a novel contribution of this research. As far as we know, there are no risk analysis publications to compare with this study's result for this topic. After comparing Holma et al. (Holma et al., 2018) and this research results, it was noted differences in the following risk and renewable energy types: The risks due to climate change are different for solar energy and hydropower between Holma's results and this research. The risk of causing climate change due to solar energy was found to be significant or somewhat significant (the risks from (Holma et al., 2018)), not significant (the risks of Holma et al. (Holma et al., 2018), but somewhat significant for this research results. Our result was close to not significant risk since the risk level estimate was 0.4. Thus, the accepted result can be taken as not significant across all risks analyses (this article results and two of those due to (Holma et al., 2018)). Among the risks of eutrophication for agriculture fuel, biogas was found to be very significant or significant (the risks from Holma et al. (Holma et al., 2018)), significant (the risks from Holma et al. (Holma et al., 2018)) and somewhat significant for this article results (0.1–0.5 risk estimate level). These results show wide differences across the different analyses. This may be due to differences of opinion between different experts.

Toxicity risks were found differ across different analyses for solar power and hydropower. Toxicity risks from solar power and hydropower were found to be somewhat significant (the risks from Holma et al. (Holma et al., 2018)) and not significant in this research case (0.0 risk estimate levels). The impacts of biodiversity or aesthetic impacts show a difference for hydropower, being somewhat significant or significant (the risks from Holma et al. (Holma et al., 2018)), significant (the risks from Holma et al. (Holma et al., 2018)) and somewhat significant (0.4 risk estimate level) for this article results. Soil depletion and soil quality, including organic matter, erosion nutrient balance, salinisation and compaction for hydropower were somewhat significant or significant (the risks from Holma et al. (Holma et al., 2018) and not significant (0.0 risk estimate level) for the current result. Water use/-water footprint for hydropower was somewhat significant or significant (the risks from Holma et al. (Holma et al., 2018)), not significant (the risks from Holma et al. (Holma et al., 2018)) and somewhat significant (0.4 risk estimate level) for this article result, which is close to not significant. Water use/water footprint for all renewables was not significant (the risks from Holma et al. (Holma et al., 2018)) and somewhat significant (0.1–0.8 risk estimate levels) for this research result. Land use (land area as a resource) risks from wind power were somewhat significant (the risks from Holma et al. (Holma et al., 2018)) and significant (wind energy/ground, 1.8 risk estimate level) or not significant (wind energy/ offshore, 0.2 risk estimate level) for this article results. Hydropower risk was found to be significant (the risks from Holma et al. (Holma et al., 2018)) and somewhat significant (0.4 risk estimate level) for this research results. Abiotic resources depletion (materials, minerals, fossil fuel) risks from solar power were significant (the risks from Holma et al. (Holma et al., 2018)), not significant (the risks from Holma et al. (Holma et al., 2018)) and somewhat significant (solar collector) or significant (solar panel) (0.4 or 1.0 risk estimate levels) for this article results. In additions, abiotic resource depletion (materials, minerals, fossil fuel) risks from hydropower were somewhat significant (the risks from Holma et al. (Holma et al., 2018)), not significant (the risks of Holma et al. (Holma et al., 2018)) and somewhat significant (0.2 risk estimate levels) for this research results. These were the only differences noted between the results of this research and those of Holma et al. (Holma et al., 2018).

The strengths of the study lay in its finding similar results as in the previous studies. Furthermore, this article is probably the first formal contribution to specific risks of climate change effects to renewable energy. The method adopted by this paper contributes to a more holistic understanding the environmental and climate change risks associated with renewable energy resources, in comparison with the existing literature. The limitations of the study that were noted were the low number of experts that participated in the risk analysis and the time taken to collect the data. The unexpected findings included the generalised evaluation, which shows the best and the riskiest types of renewable energy. Thus, generalising the whole analysis shows that field biomass energy had the most effects on the environment and was the most affected by climate change. The main hypothesis was that even though the environmental impacts of renewable energy sources (most technologies) appear small, they cannot be completely ignored (Sokka et al., 2016). This research emphasises that even if the risks of renewable energy to the environment are low, there are clear risks. In additions, climate change affects renewable energy to somewhat. This is the significance of this study showing the risks of renewable energy in some areas of Finland and for biogas in Sweden. All these studies can serve as a starting point for future research into the risks of renewable energy using broad expertise. In addition, this research result and future results can be easily incorporated into the management of renewable energy regional development.

5. Conclusions

The main finding can be summarised as follows:

Regarding the risks of climate change effects on all renewable energy resources, the least affected was ground heat source energy and the most affected was field biomass energy.

In evaluating climate change effect risks to:

- Geothermal energy resources, the least affected sources were ground heat sources and the most affected water heat exchangers.
- Bioenergy and biomass energy resources, the least affected were algae resources and the most affected was field biomass energy.
- Solar based energy resources, the least affected were solar energy/collectors and the most affected was wind energy/offshore.

In evaluating the environmental risks due to the use and production of renewable energy resources, the least risky were solar energy/collectors and the riskiest was field biomass energy.

- Field biomass energy was determined to be the riskiest to the environment among all renewable energy resources, as well having the highest risk due to climate change effects.
- For geothermal energy resources, the least risky was energy using asphalt/concrete covered areas as a heat source and the riskiest were sediment heat energy resources.
- Among bioenergy and biomass energy resources, biogas from different sources had the least effects and field biomass energy resources had the most.
- For solar-based energy resources, the one with the least effects was solar energy/collectors and one with the most effects was ground wind energy.

The best energy resources, those that had the fewest environmental effects and were the least affected by climate change effects, were solar energy/collectors and ground heat sources, respectively.

Most of the risk analysis results show similar findings with the studies by Holma et al. (Holma et al., 2018) for risks of the use and production of renewable energy to the environment. Thus, this confirms that the results of this study were very trustworthy. The unique contributions were that the risks of climate change to renewable energy resources were addressed, this has not been addressed much in other studies. The significance of the study is that it aimed to help in making sure renewables are safe for the environment leading and helping renewable energy sustainability by creating attractiveness and awareness of its risk-free facts to society compared to fossil fuels. One of the novelties of the study is that new renewable energy sources – sediment heat, asphalt heat and water heat exchangers – are considered in this study and their risks are evaluated.

In this research it was also highlighted that there are risks to the environment due to renewable energy use and production and that climate change effect risks to renewable energy clearly exist. These risks were quantified in this research. There is a clear need for a more in-depth study utilising more expert opinions. This research contributed insights to the neglected topic of risk related to renewable energy. Even if the risks of renewable energy are small in comparison with fossil fuels, they are nonetheless significant enough that they cannot be ignored. These findings are crucial to the implementation and management of renewable energy in regional energy development.

The limitations of this research were: 1) the low number of experts that participated in the risk analysis, 2) the time taken to collect the data was too long and 3) some energy systems and methods should be added and improved, e.g. PV (photovoltaic cells) battery storage and its analysis by using the LCA (Life Cycle Assessment) method and software's. Future plan of development is that to include a wide number of expertise in larger areas e.g. in several nations and collect the data in the shorter period including the missing energy storage systems. Moreover, develop the method into better well-known methods such as LCA and other software's. As well, a comparative analysis with other similar methods can be done to demonstrate the correctness of the obtained results. Currently, this study results were verified by comparing with the result by Holma et al. (Holma et al., 2018). In the future, it will be possible to expand the risk analysis by consulting more experts for data collection and performing more multidisciplinary research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgements

We acknowledge the funding received by a doctoral researcher (Nebiyu Girgibo) from the Ella and George Foundation, the University of Vaasa Foundation and the Finnish Cultural Foundation over the course of the research. Nebiyu Girgibo also received additional salary and cost support from the Academy of Finland in the Profi 4 project at the University of Vaasa. We also would like to acknowledge the University of Vaasa for providing suitable research collaborators, resources and employment. A further acknowledgement goes out to all the experts who participated in the data-gathering process, as well as to Dr Birgitta Martinkauppi and Dr Pekka Peura, who commented on and reviewed the paper and whose assistance was invaluable. In addition, we are very thankful for the anonymous reviewers and the editor-in-chief for their help and valuable comments.

Ethics approval and consent to participate

Not applicable.

Funding

Over the course of this research, the first author (Nebiyu Girgibo) received doctoral student funding from the Ella and George Foundation, the University of Vaasa Foundation and the Finnish Cultural Foundation. Additional salary and cost support for Nebiyu Girgibo came from the Academy of Finland funding in the Profi 4 project. The University of Vaasa was also acknowledged for the provision of suitable research collaborators, resources and employment.

Consent for publication

All the authors agreed and gave their consent for publication.

Appendix

Table 3
The summarised results for the risks of renewable energy to the environment: impact category, renewable energy and process, and significant category risk (comparison of Holma et al. (Holma et al., 2018) and the current research results). The dash sign (-) represents those technologies not analysed under the specific column.

The impact category in the assessment	Renewable energy sources and process	Significance category risk for 2018 (Holma et al., 2018)	Significance category risk for 2020 target level (Holma et al., 2018)	Risk estimate levels for our research findings
Climate change	Solar power	Significant or somewhat significant	Not significant	Somewhat significant (0.4 risk estimate level)
	Agriculture fuel, biogas	Significant and in the case of biogas not significant or somewhat significant	Agriculture - Not significant or rape diesel- somewhat significant Biogas - Not significant or somewhat significant	Somewhat significant for filed biomass (0.9 risk estimate level) and biogas from different sources somewhat significant (0.25 risk estimate level)
	Wind power	Somewhat significant	Not significant or somewhat significant	Somewhat significant (0.8 risk estimate level)
	Geothermal energy	-	Not significant or somewhat significant	Somewhat significant (generalised to all types of geothermal energy, risks were between 0.3 – 0.7 risk estimate levels)
	Hydro power	Somewhat significant or significant	-	Not significant (0.0 risk estimate level)
	Forest energy	Significant	Wood biomass - Significant	Significant or somewhat significant (1.25 risk estimate level)
Ozone depletion	Solar power	Somewhat significant or not significant	Not significant	Not significant (0.0 risk estimate level)
	All renewables	-	Not significant	Not significant to somewhat significant (0.0 – 0.4 risk estimate level)
Acidification	Solar power	Not significant or somewhat significant	Not significant	Not significant (0.0 risk estimate level)
	Agriculture fuel, biogas	Somewhat significant	-	Somewhat significant (0.4 risk estimate levels. Biogas was somewhat significant (0.1 risk estimate level)
	Forest energy	Somewhat significant	-	Somewhat significant (0.4 risk estimate level)
	Geothermal and wind power	-	Not significant or somewhat significant	Not significant or somewhat significant (0.0 – 0.5 risk estimate level)
Tropospheric ozone formation	Solar power	Not significant or somewhat significant	Not significant	Not significant (0.0 risk estimate level)

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Table 3 (*continued*)

The impact category in the assessment	Renewable energy sources and process	Significance category risk for 2018 (Holma et al., 2018)	Significance category risk for 2020 target level (Holma et al., 2018)	Risk estimate levels for our research findings
	Agriculture fuel, biogas	Somewhat significant	-	Somewhat significant (0.1 – 0.6 risk estimate level)
	Forest energy	Somewhat significant	-	Somewhat significant (0.3 risk estimate level)
	Geothermal and wind power	-	Not significant or somewhat significant	Not significant (0.0 risk estimate level)
Particular matter formation: impacts on health and short-term climate effects	Solar power	Not significant or somewhat significant	-	Not significant (0.0 risk estimate level)
	Agriculture fuel, biogas	Somewhat significant	Somewhat significant	Somewhat significant (0.2 – 0.8 risk estimate level)
	Wood burning /forest energy	Very significant	Very significant	-
	District heating plants	Significant	-	-
	Other forest type products/Forest energy	Somewhat significant	-	Somewhat significant (0.2 – 0.8 risk estimate level)
	Geothermal and wind power	-	Not significant or somewhat significant	Somewhat significant (0.4 – 0.8 risk estimate level)
Eutrophication	Agriculture fuel, biogas	Very significant or significant in the case of biogas	Significant	Somewhat significant (0.1 - 0.5 risk estimate level)
	Hydropower	Somewhat significant or significant	-	Somewhat significant (0.2 risk estimate level)
	Forest energy	Somewhat significant	-	Somewhat significant (0.4 risk estimate level)
Toxicity	Solar power	Somewhat significant	-	Not significant (0.0 risk estimate level)
	Agriculture fuel, biogas	Somewhat significant	Somewhat significant	Somewhat significant (0.4 – 0.6 risk estimate level)
	Hydropower	Somewhat significant or significant	-	Not significant (0.0 risk estimate level)
Impacts of biodiversity and/or aesthetic impacts	Solar power	Not significant or somewhat significant	-	Somewhat significant or not significant (0.1 risk estimate level)
	Agriculture fuel, biogas and CHP (Combined heat and power) plants	Somewhat significant	Somewhat significant	Significant to somewhat significant (0.4 – 1.8 risk estimate level)
	Wind power	Somewhat significant	Not significant or somewhat significant (Aesthetic and noise)	Somewhat significant to significant (1.2 risk estimate level)
	Hydropower	Somewhat significant or significant	Significant	Somewhat significant (0.4 risk estimate level)
	Geothermal energy/air source heat pump aesthetic impacts	Somewhat significant and (not analysed)	Somewhat significant	Somewhat significant (0.0 – 0.8 risk estimate level)
	Deadwood (forest energy)	Significant	Significant	-
Soil depletion and soil quality, including organic matter, erosion nutrient balance, salinisation and compaction	Agriculture fuel, biogas	Somewhat significant, not significant for nutrient balance	Somewhat significant	Somewhat significant (0.2 –0.7 risk estimate level)
	Solar power	-	Not significant	Not significant or somewhat significant (0.0 (solar collector) and 0.2 (solar panel) risk estimate level)
	Hydropower	Somewhat significant or significant	-	Not significant (0.0 risk estimate level)
	Forest energy	Somewhat significant	-	Somewhat significant (0.8 risk estimate level)
Water use/water footprint	Solar power	Not significant or somewhat significant	Not significant	Not significant (Solar energy/ panel, 0.0 risk estimate level) or Somewhat significant (Solar energy/ collector, 0.2 risk estimate level)
	Hydropower	Somewhat significant or significant	Not significant	Somewhat significant (0.4 risk estimate level)
	Geothermal power	Somewhat significant or significant	Somewhat significant	Somewhat significant (0.1 – 0.6 risk estimate levels)
	CHP production	Somewhat significant	Not significant	-
	All renewables	-	Not significant	Somewhat significant (0.1 – 0.8 risk estimate levels)
Land use (land area as a resource)	Wind power	Somewhat significant	-	Significant (wind energy/ground, 1.8 risk estimate level) or not significant (wind energy/ offshore, 0.2 risk estimate level)
	Hydropower	Significant	-	Somewhat significant (0.4 risk estimate level)
	Agriculture fuel	Significant	-	Significant (1.0 risk estimate level)
	Biogas	Significant	Not significant or somewhat significant	Somewhat significant (0.2 – 0.3 risk estimate levels)
Lowering of groundwater levels	All renewables	-	-	Between not significant and somewhat significant (0.0 – 0.8 risk estimate levels)

(*continued on next page*)

Table 3 (*continued*)

The impact category in the assessment	Renewable energy sources and process	Significance category risk for 2018 (Holma et al., 2018)	Significance category risk for 2020 target level (Holma et al., 2018)	Risk estimate levels for our research findings
Abiotic resource depletion (materials, minerals, fossil fuel)	Solar power	Significant	Not significant	Somewhat significant (solar collector) or significant (solar panel) (0.4 or 1.0 risk estimate levels)
	Hydropower	Somewhat significant	Not significant	Somewhat significant (0.2 risk estimate levels)
	Geothermal power	Somewhat significant	Not significant or somewhat significant	Somewhat significant up to significant (0.4 up to 1.0 risk estimate levels)
	Wind power	Somewhat significant	Not significant or somewhat significant	Somewhat significant (0.8 risk estimate level)
	All energy that requires infrastructure	Somewhat significant	-	-
	All renewables	-	Not significant	Not significant up to significant (0.0 up to 1.0 risk estimate levels)
Radiation	All renewables	Not significant	Not significant	Not significant (0.0 risk estimate level), somewhat significant (0.2 risk estimate level) for hydropower
Plants, pests and diseases	Agriculture fuel, biogas	Significant, or somewhat significant for Barley and wheat ethanol	Agricultural fuel was somewhat significant and biogas was not analysed	Somewhat significant (0.2 – 0.4 risk estimate levels)
	Forest energy	Somewhat significant	-	Somewhat significant (0.8 risk estimate level)
Effects on birds and other animals	All renewables	-	-	Between significant and not significant (0.0 – 1.4 risk estimate levels)

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