scientific reports

OPEN

Integrating Pollutant registers for the climate change risk evaluation of industrial companies in Australia, Europe and North America

Szilárd Erhart[1], Sándor Szabó[1] & Kornél Erhart[2]

We present a methodology to develop the integrated climate change transition and physical risk assessment of industrial companies in Europe, Northern America and Australia. There is an increasingly important need for effective large-scale climate change risk assessment solutions with more governments aligning their company reporting regulations with the Task Force on Climate-related Financial Disclosures recommendations. In this paper, we measure key aspects of climate change risks of industrial firms on the globe and vice versa. The study provides valuable insights into climate risk exposure for companies, investors, and consumers, offering a pioneering approach by integrating data from major international registers. We analyse data from 70,000 companies and their 170,000 plants, which report to fragmented Pollutant Release and Transfer Registers and Greenhouse Gas Reporting Programs. For our assessment, transition risks are measured in terms of reported greenhouse gas emissions, while physical risks calculated for all company plant locations in terms of historical cooling energy needs, flood exposure and photovoltaic power potential. We show that climate change transition and physical risks are not correlated, therefore climate change risks are variably felt across different factors. The research contributes to the evolving landscape of climate risk management and highlights the need for standardized methodologies in the face of impending regulatory changes.

Albeit climate-related financial disclosure is becoming a norm with more governments in developed countries adopting the recommendations of the Task Force on Climate-related Financial Disclosures (TCFD), not all companies are preparing strategies, selecting key performance indicators and setting targets to contribute to reaching the global objective of minimizing global warming to 1.5C by 2050. Firms TCFD/climate risk disclosures are prone to become a ceremonial practice with 'cheap talk', 'greenwashing' or 'cherry-picking' and reporting of primarily non-material climate risk information[1,2].

Pollutant Release and Transfer Registers (PRTRs) and Greenhouse Gas Reporting Programs (GHGRPs) are increasingly used as fundamental data sources for corporate climate and environmental footprint research[3–6]. National pollution registers offer a nuanced examination of local pollution[7], but neglect to offer international assessment. Earlier studies on PRTRs focused on the chemical footprint assessment of point-source emissions and calculated impact potentials for human toxicity and ecotoxicity as key metrics to measure chemical footprints on the national, pollutant and facility level[3,8,9]. The Japanese PRTR was used for an input-output analysis and decomposition analysis, to measure the socio-economic factors of changes in toxicological footprint[10]. Earlier carbon footprint methods helped assess resource consumption, CO_2 emission and related climate change risk separately, but usually neglected integrated assessment of other indicators[11].

The improvement of various physical and transition risk assessment methods has become an urgent task for the scientific research community, however, there is still an obvious gap between the contribution of the scientific research community and enterprise needs[12]. Investors and regulators require as well reliable estimates of physical climate risks for decision-making[13].

The methodology developed by the present study gives corporate-level insight on the potential corporate strategies towards managing these risks and can give policy makers insight how to internalise the diverse interest of corporate stakeholders.

[1]Joint Research Centre, European Commission, Ispra, Italy. [2]Budapest, Hungary. ✉email: szilard.erhart@ec.europa.eu

In this paper, we discuss the relevance and opportunities of developing a standardized methodology for assessing climate change transition together with physical risks in an integrated framework for a sufficiently large company population.

In Europe, the reporting of climate change risks is going to be not only a norm, but a legal obligation from the 2024 financial year, with first reports to be published in 2025. The Corporate Sustainability Reporting Directive (CSRD) will require from 50,000 companies to disclose information on environmental and social impacts, including all large companies and all listed companies (except listed micro-enterprises)[14].

In this paper, we discuss the exposure of industrial companies to the two major categories of climate risks: (i) transition risks and (ii) physical risks[15]. Transition risks associate with the extent and speed at which an organization adapts to climate change, e.g. reduces greenhouse gas emissions and manages its transition to renewable energy. Physical risks stem from the physical impacts of climate change, including extreme weather events, such as heat waves and floods.

Physical risks can directly damage assets or indirectly harm production by causing supply chain disruption. Hence, physical risks may have financial implications for organizations. Rising temperature at work also increases the likelihood of heat-related illnesses and limit workers productivity, especially due to workers low risk perception of heat stress[16,17].

Transition risks impact on firms indirectly by influencing investors' and clients' attitudes towards asset classes with different climate risk profile. In recent years, firms with the lower climate transition risk exposures tended to perform better financially[18]. The energy used to power people's lives and livelihoods and to fuel global trade and industry produces about three-quarters of global greenhouse gas (GHG) emissions. A well-managed retirement of energy generation plants with the largest global warming potential and a massive scale-up in clean energy are essential to achieving the Sustainable Development Goals and the targets of the Paris Agreement[19]. In particular, the transition from fossil fuels to renewable power for heating and cooling is a cornerstone of the sustainable energy transition. Companies will need to transition an increasing share of their energy generation to low emission alternatives such as solar to meet emission-reduction goals[15]. Furthermore, protective measures against flood risks for example can help reduce the extent of inundated areas as an effective adaptation strategy leading to substantially lower negative impact for firms[20].

The International Energy Agency (IEA) points out that the private sector have to play a central role in the unprecedented levels of climate related investments. Beyond government incentives and regulations it is important to give a corporate level analysis how the losses and the gains investing in climate mitigation are distributed amongst the companies. Climate and environmental services are often regarded as public goods leading to over-exploitation or under-investments. If the gains are not borne by the potential financing companies it gives a rise to free riding strategies.

The significant novelty of this study is that it allows to understand and measure climate change risk exposure before reporting obligations become effective for a substantial number of companies, their investors and consumers.

To the best of our knowledge, this is the first study that integrates information from the major Pollutant Release and Transfer Registers covering more than 30 countries (AU, CA, EU27 + UK, IS, RS, NO, CH, US) on the company facility level (Figure 1). Furthermore, we integrate further data from repositories on point-source greenhouse gas emissions.

About 10,000 foreign companies are expected to be required to report according to the EU CSRD rules, mostly from the Unites States (31%), Canada (13%), United Kingdom (11%), Japan (8%) and Australia (6%)[21]. All these countries are covered in this study except Japan. Companies subject to the CSRD will have to report according to European Sustainability Reporting Standards (ESRS).

We show that climate change transition and physical risks are not correlated, therefore climate change risks are variably felt across different factors. The research contributes to the evolving landscape of climate risk management and highlights the need for standardized methodologies in the face of impending regulatory changes.

The rest of the paper is structured as follows. The Section "Results" presents empirical findings on climate indicators, correlation analysis of various climate risks at the corporate facility level. Section Data and Methods details our data sources empirical set-up and methodological framework. The "Discussion" explains the limitations of our empirical set-up. The Summary section summarizes the key research questions, findings and policy recommendations of our study.

Results

Climate change can impact companies via several channels. The seriousness of consequences can be underestimated, if only the climate change transition risks from GHG emissions are calculated. The consequences from physical risks, for example from material damages to company properties, machinery or labour force, the related production, financial or reputation losses can be vast and are dependent on the location of company facilities.

Therefore, we calculated risks both in terms of global warming impact potentials and physical risks (flood risk, heat risk) of large industrial companies together with climate-transition related opportunities (photovoltaic potential) in Europe, in Northern America and Australia. Impact potentials are measured in terms of carbon dioxide equivalents (CO_2eq) for the global warming potentials, flood risk in terms of the depth of historical water discharge (meter), heat risk in terms of cooling degree days (CDD) and climate-transition related opportunities in terms of renewable energy potentials at plants (long term average daily total of photovoltaic power potential, kWh from a grid connected 1 kWp optimally tilted power plant).

Fig. 1. Location of industrial company sites in the sample (with the description of the data sources)[a]. The map was created by the authors with Google Looker Studio, https://lookerstudio.google.com, Map data 2024 Google, Imagery 2024 NASA. [a] Data providers/Reporting programs and Databases/Country and Region. European Environment Agency (EEA)/ EU Pollutant Release and Transfer Register/ European Union (EU). Environmental Protection Agency (EPA)/ Toxic Release Inventory (TRI)/ Unites States (US). Environmental Protection Agency (EPA)/ Greenhouse Gas Reporting Program (GHGRP)/ Unites States (US). Australian Government/ National Pollutant Inventory (NPI)/ Australia (AU). Government of Canada/ Greenhouse Gas Reporting Program (GHGRP)/ Canada (CA). Clean Energy Regulator (CER)/ National Greenhouse and Energy Reporting (NGER)/ Australia (AU). Australian Government/ National Pollutant Release Inventory (NPRI)/ Australia (AU).

Different climate change risk indicators cannot be directly compared, as they are measured on different scales and in different units. Hence, we also converted original values into normalized scores by calculating percentile ranks so as to lessen the problem of outliers[22].

Figure 2 presents a geographic map of the investigated climate risks by country as average normalized scores. White to light grey colour and higher score mean lower climate change risk, while dark grey to black colour and lower score values mean higher risks.

Heat risk is estimated to be higher for firms in the US, in the Mediterranean countries of Europe and in Australia, while lower for firms located in Canada and Northern European countries (UK, Sweden, Norway). In the US the plants most exposed to heat risks are located in the Southern States, while in Europe, in Spain and Italy.

On the continental level industrial firm locations in Central Europe have been most vulnerable to flood events in the past. More detailed visualisation on the plant level data reveals that there are several plants in Eastern States of the US which are exposed to higher level of flood risks. (See the detailed maps in the Appendix: Figs 4, 5, 6, 7).

On average, the largest average global warming potential was calculated for industrial plants in Iceland, the United States, Denmark and Greece. Detailed maps in the Annex show that CO_2 emissions of industrial plants are concentrated in Central Europe, in the UK and Eastern America.

The photovoltaic potential is the highest in Australia and Spain, while the lowest in Northern Europe.

Correlation analysis

We documented that there are differences in the exposure to different climate change risks at the country level. It is, however, an important issue of climate risk management, whether and to what extent different climate risks are interlinked and associated at the company plant level.

Figure 3 presents the Pearson correlation ratios. We found that pairwise Pearson correlation ratios are in most cases low, close to zero, although significant. This implies that climate change risks are variably felt across different factors, some companies will be exposed more to heat risks, others to flood risks. The only exemption is the relationship of heat risks and photovoltaic potential, for which the Pearson correlation is positive 0.57 and significant. Positive correlation means association here, not causality, as none of these two variables causes changes in the other, but the exposure to sunlight is the source of energy that can either increase temperature at the company locations or can be converted into electric energy by solar panels.

Table 4 in the Appendix presents pairwise Pearson correlation ratios of the analysed climate indicators by countries. In Hungary (0.82), Spain (.61), Luxembourg (.58), Portugal (.52), Australia (.52), Czech Republic (.51), France (.51) were the calculated correlation ratios between the heat risk and photovoltaic potential the highest at the company location. Although, electricity can be transmitted, if the most productive geographical regions for

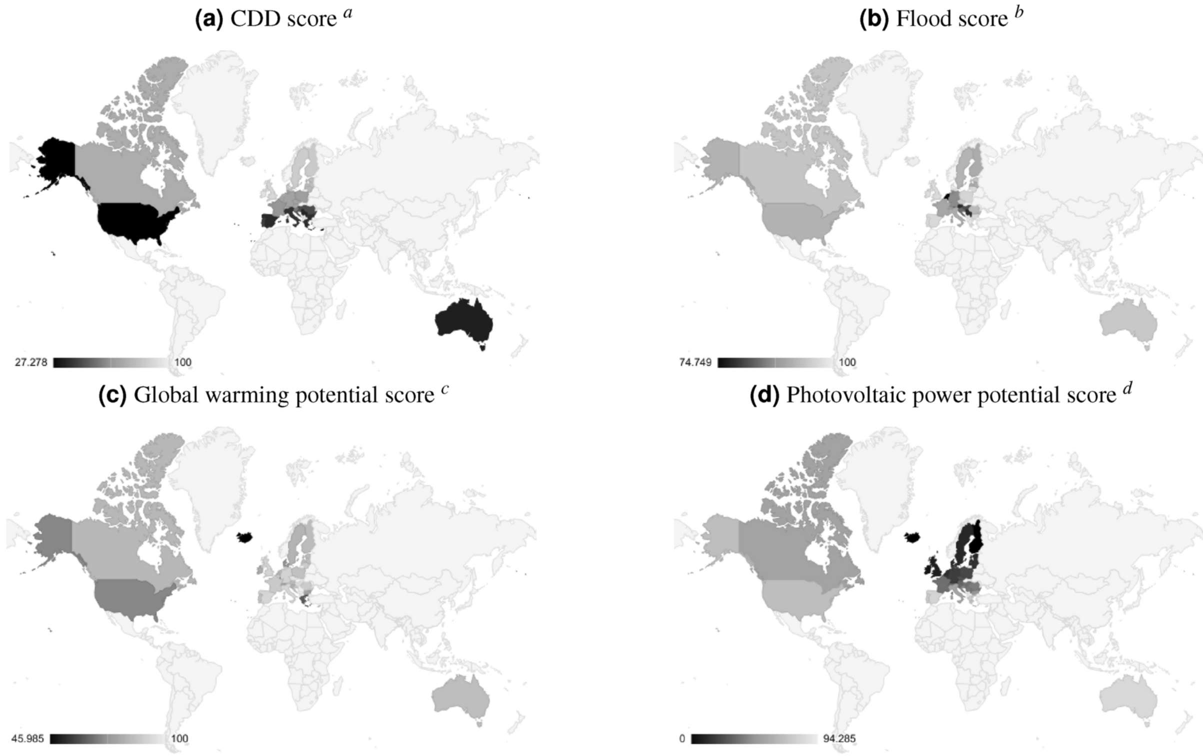

Fig. 2. Climate change transition risks and physical risks by country. Normalized values (0 - highest risk/lowest potential, 100 - lowest risk/highest potential, arithmetic mean of all reporting entities in the given country). The map was created by the authors with Google Looker Studio, https://lookerstudio.google.com, Map data 2024 Google, Imagery 2024 NASA. [a] Heat risk scores are normalized (CDD) - Cooling Degree Days values. [b] Flood risk scores are normalized flood risk values in meter (m). [c] Global warming potential scores are normalized reported and calculated CO_2 equivalents in tonnes. [d] PV potential scores are normalized long term average daily total of photovoltaic power potential values in kilowatthour (kWh), of a optimally tilted 1kWp solar power plant. The visualized score values for each country in the sample are the arithmetic mean for the reporting companies in the given country. More detailed company plant level maps are presented in the Appendix.

solar energy generation are far away from the place of use, network infrastructure cost and transmission losses may increase costs of adaptation to climate change physical risks. Power loss and costs of renewable energy deployment can increase as a function of the power generated and the transmission distance.

Data & methods

Our methodology and empirical analysis are based on two types of data sources: (i) on siloed plant level pollution registers, (ii) on historical data from Geographic Information Systems on physical risks (heat risk, flood risk) and climate change transition related opportunities (photovoltaic power potential). We relate these information sources to calculate different types of climate risk measures at the company plant level.

Data

Our company location and global warming potential data is retrieved from Pollutant Release and Transfer Registers and greenhouse gas reporting program repositories in more than 30 countries (Australia, Canada, European Union (EU) Member States and further EU neighbouring countries reporting to the European Pollutant Release and Transfer Register, United States) (Table 1). These registers contain annually aggregated emission data by company plants. We used the 2019 observations for our analysis due to delays in reporting.

The Protocol on Pollutant Release and Transfer Registers (PRTRs) was agreed on by international parties to register environmental footprints across regions and times[6].

The European Industrial Reporting dataset of the European Environment Agency (EEA) contains the location and administrative data for the largest industrial complexes in Europe, releases of regulated substances to all media reported under the European Pollutant Release and Transfer Register (E-PRTR) and as well as more detailed data on energy input and emissions for large combustion plants (reported under the Industrial Emissions Directive Art.72). The E-PRTR reporting covers 91 key pollutants including greenhouse gases. While E-PRTR regulation registers about 90% of the point-source emissions of the listed pollutants, it should be noted that a high share of greenhouse gases CH4 and N2O (14-38%) is released from non-E-PRTR activities and not covered by our analysis. Various datasets, including most EU Member States (MS) air pollutant and greenhouse

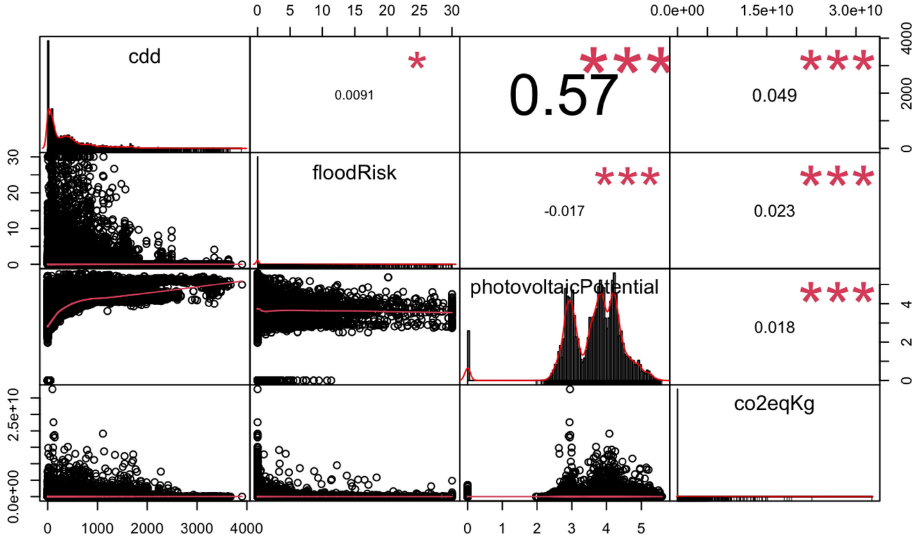

Fig. 3. Combined figure of Pearson correlation ratios and significance levels (upper right cells), indicator histograms (diagonal cells), pairwise scatter plots of indicators (lower left cells). [a] Heat risk (cdd) - Cooling Degree Days. [b] Flood risk (m) - meter. [c] Photovoltaic potential, long term average daily total of (kWh) - kilowatthour from optimally tilted 1kWp panel. [d] GHG (CO_2eqKg) - CO_2 equivalent in kg. 2019 observations have been used for the GHG emissions.

Institution	Reporting program, database	Country
European Environment Agency	EU Pollutant Release and Transfer Register	European Union
Environmental Protection Agency	Toxic Release Inventory	Unites States
Environmental Protection Agency	Greenhouse Gas Reporting Program	Unites States
Australian Government	National Pollutant Inventory	Australia
Government of Canada	Greenhouse Gas Reporting Program	Canada, United States
Clean Energy Regulator	National Greenhouse and Energy Reporting	Australia
Australian Government	National Pollutant Release Inventory	Australia

Table 1. Company location and greenhouse gas data sources of the study by institution, reporting program and country. Abbreviations of institutions, programs and databases European Environment Agency (EEA) Environmental Protection Agency (EPA) Toxic Release Inventory (TRI) Facility Level Information on Greenhouse Gases Tool (FLIGHT) National Pollutant Inventory (NPI) Clean Energy Regulator (CER) National Greenhouse and Energy Reporting (NGER) Greenhouse Gas Reporting Program (GHGRP) - There are two separated programs with identical program names for Canada and the United States. National Pollutant Release Inventory (NPRI).

gas inventories, identify cattle rearing as an important source of ammonia and methane releases. The E-PRTR does not include the majority of these releases[23].

The US Environmental Protection Agency (EPA)'s PRTR repository is called Toxic Release Inventory (TRI). The EPA collects information on greenhouse gases separately from other pollutants. Large emitters report these under the Greenhouse Gas Reporting Program (GHGRP). Approximately 8,000 fuel and industrial gas suppliers, and CO_2 injection facilities in the United States are required to report their greenhouse gas emissions annually. The GHGRP does not represent total U.S. GHG emissions, but provides facility level data for large sources of direct emissions, thus representing the majority of U.S. GHG emissions. The reported emissions exclude biogenic CO_2 and only emissions from exceeding 25,000 metric tons CO_2eq per year are reported, (https://www.epa.gov/ghgreporting/ghgrp-reported-data.) The EPA aggregates the GHGRP information and publishes data via the Facility Level Information on Greenhouse Gases Tool (FLIGHT). To merge the TRI and FLIGHT databases for our analysis we used the Facility Registry Service Id (FRSID) of EPA, which was available in both the TRI and FLIGHT datasets.

The National Pollutant Inventory (NPI) is the Australian PRTR tracking pollution, and ensuring transparency and public access to information. Under the Australian National Greenhouse and Energy Reporting (NGER) Scheme, corporations that meet certain thresholds must also report to the Clean Energy Regulator (CER) their emissions, energy production and energy consumption each financial year. In Australia the range of emission sources includes: the combustion of fuels for energy, fugitive emissions from the extraction of coal, oil and gas, industrial processes (such as producing cement and steel) and waste management, (https://www.dcceew.gov

.au/climate-change/emissions-reporting/national-greenhouse-energy-reporting-scheme). For our research the facility identifier has been used to merge the Australian NPI and NGER datasets.

The National Pollutant Release Inventory (NPRI) is Canadas public inventory of pollutant releases, disposals and transfers. It tracks over 300 pollutants from over 7,000 facilities across Canada. The Canadian Greenhouse Gas Reporting Program (GHGRP) collects information on greenhouse gas (GHG) emissions annually from facilities across Canada. It is a mandatory program for those who meet the requirements. Furthermore, facilities that emit 10 kilotonnes or more of GHGs, in carbon dioxide (CO_2) equivalent (eq.) units, per year must report their emissions to Environment and Climate Change Canada. The information is collected under section 46 of the Canadian Environmental Protection Act. 1,814 facilities reported their greenhouse gas (GHG) emissions for 2022 to Environment and Climate Change Canada, totalling 293 megatonnes (Mt) CO_2 eq. The GHG emissions reported by facilities for 2022 represent 41% of Canadas total GHG emissions (708 Mt in 2022) and 62% of Canadas industrial GHG emissions, (https://data-donnees.az.ec.gc.ca/data/substances/monitor/greenhouse-gas-reporting-program-ghgrp-facility-greenhouse-gas-ghg-data/). The facility identifier has been used to merge the Canadian NPRI and GHGRP databases. The 'NPRIID' is a unique National Pollutant Release Inventory identifier.

Our final database covers almost 170,000 plant locations in the reporting countries. The coordinates of plants (latitude, longitude) were used to collect information on climate change physical risks. By using the exact coordinates our analysis can provide a more accurate climate risk assessment than studies using addresses of firm headquarters which do not necessarily identify locations of plants precisely[20].

The source of the company plant heat risk information was based on geographic sampling the historical information systems of the globe (Table 2). Our input cooling degree days map was originally computed using meteorological parameters from the Global Land Data Assimilation System (GLDAS) ver. 2 (0.25 degree global gridded resolution)[24]. The cooling degree days dataset covers 49 years over the period 1970-2018.

The source of flood risk data was the Joint Research Centre's long-term dataset of river discharges in the Global Flood Awareness System (GloFAS)[25]. Flood risk values indicate water depth (in m) from river discharges. All flood-prone areas are then merged by the Joint Research Centre to create continental flood hazard maps for different return periods at 30 resolution (approximately 1 km at the Equator).

The World Bank Group's Global Solar Atlas was used to sample photovoltaic power potential at company plants, more precisely the average daily total photovoltaic power potential (PVOUT) in kWh (kilowatthour) of a free-standing 1 kW PV system at optimum tilt at the company locations. The clear-sky irradiance calculated is coupled with the cloud index to retrieve the all-sky irradiance values. The resolution of solar resource data is 30 arcsec (nominally 1 km).

Methods

In this study global warming impact potentials (GWP) in carbon dioxide equivalents (CO_2eq) of direct point-source pollutant releases are analyzed. In some of the countries in our sample, the GWP information is calculated and provided by the authorities (CA, US and AU).

$$GlobalWarmingPotential(GWP) = \sum_i E_i \times GWP_i \quad (1)$$

For the EU+ countries the European Environment Agency (EEA) publishes releases by pollutant in the European Pollutant Release and Transfer Register (E-PRTR), which can be used to calculate impact potentials. Here, the GWP has been calculated as recommended by the Intergovernmental Panel on Climate Change (IPCC). The emissions in kilograms of substances (i) in the E-PRTR have been multiplied by their global warming potential value factors, and aggregated across all substances (Equation 1). Six air pollutants are classified in the E/PRTR as GHGs, similarly to the Kyoto Protocol, i.e. Carbon dioxide (CO_2), Methane (CH4), Hydro-fluorocarbons (HFCs), Nitrous oxide (N2O), Perfluorocarbons (PFCs), Sulphur hexafluoride (SF6).

Geographic sampling was applied to collect climate change physical risk values from multiple layers at specified company plant location sampling points from the thematic maps detailed in the previous subsection on data.

Normalized values of the four climate change physical risk indicators values (Table 3) were calculated as percentile ranks so as to lessen the problem of outliers[22]. To generate sector agnostic scores the normalized values were calculated in relation to all peers regardless of the industry.

Discussion

There are obstacles to the geographic sampling and overlaying method we proposed here to calculate climate change physical risks. One obstacle of our approach is that not all companies are covered by the registers we

Physical risks and climate-related opportunities	Data source	Resolution
Heat risk	Global Land Data Acquisation System	25 km
Flood risk	Joint Research, Centre	1 km
Photovoltaic power potential	The World Bank Group	1 km

Table 2. Coordinate level climate risk information sources.

used. Another obstacle to precise calculations is that PRTR databases do not register emissions below reporting thresholds. Reliability of data could be affected by the errors of facility location reporting.

The resolution of the geographic information systems we used for our assessment is also limited. This can increase the uncertainty of geographic sampling calculations and limit precise judgements in some cases. The resolution of the historical flood information was approximately 1 km. In flood risk management few hundred meters can make significant difference in terms of flood vulnerability, since elevation, dams or other built and natural barriers can create conditions that the flood risk significantly varies within a 1 km X 1 km geographic cell.

We draw attention of the readers that some industries are not covered by our analysis, because PRTRs and greenhouse repositories cover usually point-source emissions, but not diffuse emissions from for example agricultural activities or transportation[26].

The usability of our methodology could be further enhanced by using real-time or projected information on climate change risks. Integration of additional indicators like the estimations of other risks like extreme weather events or further categories of renewable energy (tidal, geothermic, wind, etc.) could lower the uncertainty of our estimations.

The precision of our methodology at the company level for environmental assessment or rating is hindered by the well-known problems of company registers. For example, reporting on company ownership or business activity is not mandatory, hence aggregation of climate risk is not always possible at the final parent company level. Consequently, requirement of reporting parent company, business activity information could help increase the usability of the PRTRs for environmental rating.

When merging the Toxic Release Inventory and GHG databases of the US Environmental Protection Agency, we recognized that the relation of facility identifiers and pollutant release identifiers is 1:m, there have been more pollutant release identifiers for the same facility identifiers. There are 114 facility identifiers where at least 2 facilities report with different pollutant release identifiers to the TRI. In such cases, we have loaded GHG observations for all records of facility identifiers, even if the pollutant release identifier was different. This implies double counting for about 0.2% of the sample, the readers have to be aware of. Reallocation of GHG data could be possible if the entities reported the allocation of GHG between different pollutant release identifiers.

Pollutant Release and Transfer Registers (PRTRs) and Greenhouse Gas Reporting Programs (GHGRPs) have been identified as fundamental data sources for the research of corporate climate and environmental footprints[3–6]. Despite their importance in local pollution assessment, by using only fragmented National pollution registers it is impossible to gain international comparison and insight. Our research offers the opportunity for international macroscopic comparison with coordinate level granularity by the integration of fragmented national registers[7]. Furthermore, we broadened the scope from chemical footprint assessment of point-source emissions to climate change physical hazards[3,8,9]. Earlier carbon footprint methods helped assess resource consumption, CO_2 emission and related climate change risk separately, but usually neglected integrated assessment of other indicators[11].

This research improves various physical and transition risk assessment methods, which was identifed as an urgent task for the scientific research community[12]. Furthermore, our methodological advancements support investors and regulators in finding reliable and feasible estimates of physical climate risks for decision-making[13].

Recent research on PRTRs[6] investigated empirically whether and to what extent the GHG indicators can be used as indicators of the overall environmental performance at the industrial facility level in Europe. Our results confirm that the carbon footprint of industrial organizations is not an overall climate change risk and environmental performance indicator. In addition, the seriousness of global warming consequences can be underestimated if only the weight of pollutants is used[27]. For example, CO2 as the referene gas for greenhouse gases, has a global warming potential (GWP) of 1 by definition, while Methane (CH4) is estimated to have a GWP of 27-30 over 100 years and Nitrous Oxide (N2O) has a GWP 273 times that of CO2 for a 100-year timescale.

For some countries in our sample (LT, CY, BE, LV, EE, GR) the Pearson correlation ratio between the heat risk measured in cooling degree days and the photovoltaic potential in terms of kWh was negative and significant in the range from -0.3 to -0.8. This implies that results of intuitive positive correlation in general between the two variables at company facility locations can be place-variant and should be interpreted with caution.

Summary

This research paper introduces a novel methodology for the integrated assessment of climate change transition and physical risks together with climate-related opportunities associated with industrial plants across Europe, Northern America, and Australia. As global governments align reporting regulations with climate-related financial disclosure recommendations, the study becomes crucial for understanding and measuring key aspects of climate-related risks and climate-related opportunities. Analyzing data from 70,000 companies and their 170,000 plants reporting to Pollutant Release and Transfer Registers and Greenhouse Gas Reporting Programs, the research measures transition risks through reported greenhouse gas emissions, physical risks through historical cooling energy needs, flood exposure and climate-related opportunities in terms of photovoltaic power potential.

The study's pioneering approach, integrating information from major international registers, offers valuable insights into and comparable indicators related to climate risk exposure and opportunities before reporting obligations become legally mandated for a substantial number of companies. Notably, the research uncovers a lack of strong correlation between climate change transition and physical risks, emphasizing the challenges in managing climate change risks and opportunities at the company level. As climate-related disclosure becomes a norm in developed economies, this research contributes to the evolving landscape of climate risk management and underscores the importance of standardized methodologies in the face of impending regulatory changes.

Our study identified recommendations for policy and industry, and specific avenues for future research. Increasing transparency and precision of corporate locations in corporate registers could help improve the accuracy of estimating and forecasting climate risks and opportunities for companies. In the same vein, calculation and publication of higher-resolution thematic geographic maps by international organisations could reduce errors of climate risk calculations by lowering the uncertainty of geographic sampling and support more precise corporate risk management.

We highlight that some industries and non-point-source (diffuse) emissions are not covered by the PRTRs from agricultural activities or transportation[26]. Future modification of reporting requirements and related research could improve climate risk assessment of these activities.

The data sources in our study are updated annually, hence the usability of our methodology could be further enhanced by the integration of near-real-time information on climate change risks and opportunities. Furthermore, broadening the scope of the research to further climate related risks (extreme whether events) and opportunities (tidal, geothermic, wind, etc.) could lower the uncertainty of our estimations.

The precision of our methodology at the company level for climate risk evaluation or related sustainability rating is hindered by the lack of information on business identifiers and company ownership. Standardized reporing requirement of these indicators by regulatory bodies could support the aggregation of climate risks at the final parent company level.

Data availability

The study is based on publicly available data sources as discussed in the data section. Furthermore, the tables in the study will be publicly available in the Mendeley repository upon publication of the study. Erhart, Szilárd (2024), XXX, Mendeley Data, V1, doi: 10.17632/bcw3b2jcxb.1. The data of this research paper has been also injected into the online Corporate Sustainability assessment platform project (R6) submitted to the European Innovation Council Accelerator program (https://www.r6bros.eu) in 2024. The R6 platform evaluates 70,000 companies in 30+ countries according to the the EU Corporate Sustainability Reporting Directive (CSRD), European Sustainability Reporting Standard (ESRS), United Nation Sustainable Development Goals (SDGs). Search is possible with company name or International Security Identification Number (ISIN) for listed firms.

Appendix

Descriptive statistics

There are almost 70,000 plants in our sample (Table 3). Cooling degree days (CDD), our heat risk measure varies in the range of 0 and 3,904 CDD calculated from the historical data in the period 1970-2018[24].
Flood risk minima and maxima was 0 meter and 30 meters, respectively.
See Table 4; Figs. 4, 5, 6, 7.

Statistic	N	Mean	St. Dev.	Min	Max
Heat risk (CDD) [a]	69,028	397	491	0	3,904
Flood risk (m) [b]	69,028	0.4	2.1	0.0	30.0
PV potential (kWh, 1 kWp) [c]	69,028	3.6	0.8	0.0	5.6
GHG (CO_2eq tonnes) [d]	69,028	66,852	495,241	0	32,700,000

Table 3. Descriptive statistics. [a] Heat risk (CDD) - Cooling Degree Days [b] Flood risk (m) - meter [c] PV potential (kWh) - long term average daily total of kilowatthour from optimally tilted grid connected 1kWp panel [d] GHG (CO_2eq tonnes) - CO_2 equivalent in tonnes 2019 observations have been used for the GHG emissions.

	countryCode	n	CDD_PV[a]	CDD_FL[b]	GHG_CDD[c]	GHG_FL[d]	GHG_PV[e]
1	LT	98	-0.80	0.10	0.00	0.09	-0.08
2	CY	62	-0.52		-0.42		0.21
3	BE	880	-0.50	0.06	-0.02	-0.01	-0.06
4	LV	60	-0.44	-0.33	0.04	-0.06	-0.07
5	EE	107	-0.37	0.20	0.17	-0.06	-0.05
6	GR	108	-0.32	0.00	-0.12	-0.04	-0.10
7	IE	466	-0.03	0.04	0.02	0.07	0.05
8	FI	646	-0.02	0.11	0.00	0.10	-0.02
9	HR	123	-0.00	0.07	0.01	-0.02	0.03
10	AT	357	0.06	0.00	0.06	-0.01	0.01
11	RS	174	0.10	0.11			
12	CA	7153	0.13	-0.00	-0.02	0.01	-0.01
13	NL	948	0.15	0.06	-0.07	-0.06	0.13
14	CH	235	0.16	0.16	-0.11	0.03	0.09
15	BG	195	0.20	0.09	0.11	-0.02	0.06
16	DK	282	0.25		-0.03		-0.10
17	PL	1488	0.31	0.03	0.03	-0.01	-0.01
18	DE	5421	0.37	0.11	0.06	0.01	-0.02
19	IT	4068	0.39	0.05	0.03	-0.01	0.08
20	GB	5381	0.40	0.09	-0.00	-0.00	-0.03
21	US	23215	0.41	-0.03	0.04	0.03	0.02
22	SE	604	0.45	-0.01	-0.16	-0.01	-0.14
23	SI	147	0.48	-0.13	-0.07	-0.02	-0.04
24	RO	745	0.48	0.07	0.03	-0.01	0.04
25	FR	3190	0.51	0.05	-0.00	-0.01	0.07
26	CZ	2681	0.51	0.04	0.02	-0.00	-0.07
27	AU	4519	0.52	0.02	0.10	-0.02	-0.14
28	PT	625	0.58	0.07	-0.09	0.12	0.12
29	LU	35	0.58		0.37		0.23
30	ES	4187	0.61	0.08	-0.06	0.01	-0.05
31	HU	821	0.82	0.05	-0.10	-0.01	-0.06
32	IS	19					
33	MT	18					0.07

Table 4. Pairwise Pearson correlation coefficients of plant level climate change indicators by countries. Normalized values were used to calculate correlation ratios. [a]CDD_PV: Cooling Degree Days vs. Photovoltaic Power Potential [b]CDD_FL: Cooling Degree Days vs. Flood Risk [c]GHG_CDD: Global Warming Potential vs. Cooling Degree Days [d]GHG_FL: Global Warming Potential vs. Flood Risk [e]GHG_PV: Global Warming Potential vs. Photovoltaic Power Potential 2019 observations have been used for the GHG emissions.

Fig. 4. Flood exposure of industrial company sites in the sample in meter. The map was created by the authors with Google Looker Studio, https://lookerstudio.google.com, Map data 2024 Google, Imagery 2024 NASA. White bubbles on the map indicate company facilities without historical flood risk, while blue bubles indicate company facility locations with historical flood risk.

Fig. 5. Photovoltaic potential of industrial company sites in the sample as the long term average daily total of kWh, of an optimally tilted 1 kWp panel. The map was created by the authors with Google Looker Studio, https://lookerstudio.google.com, Map data 2024 Google, Imagery 2024 NASA. The colour scale of the map starts with light gray (highest photovoltaic potential) and ends with black (lowest photovoltaic potential).

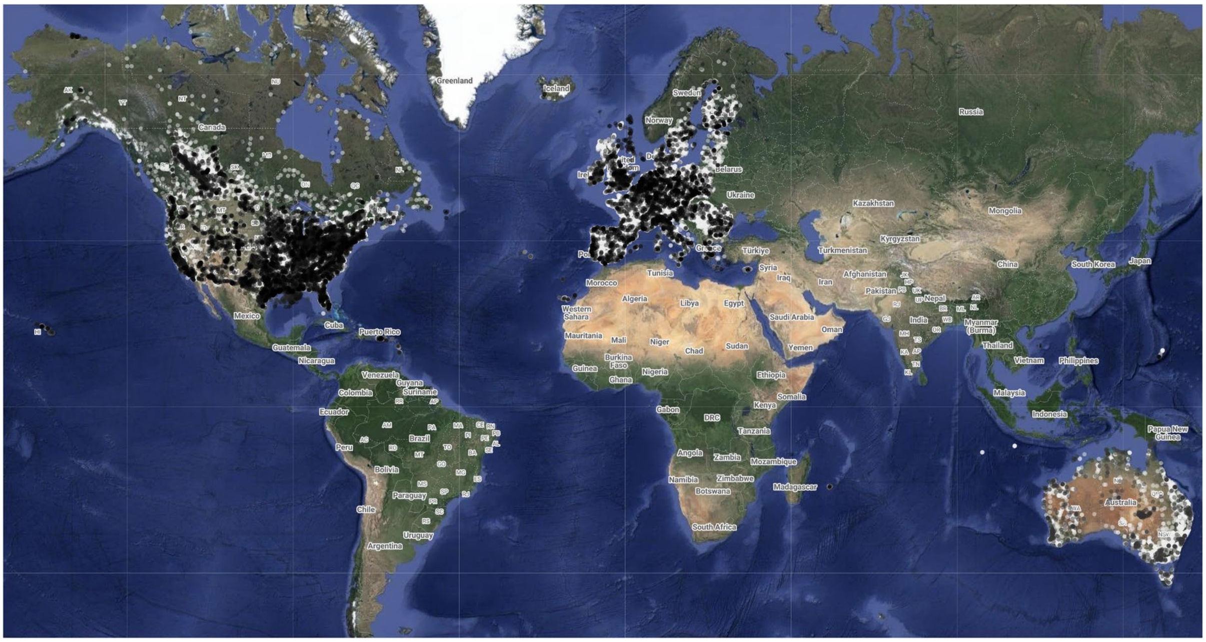

Fig. 6. Greenhouse gas emission of industrial company sites in the sample in CO_2 equivalents. The map was created by the authors with Google Looker Studio, https://lookerstudio.google.com, Map data 2024 Google, Imagery 2024 NASA. The colour scale of the map starts with light gray (lowest GHG emission) and ends with black (largest GHG emissions). 2019 observations have been used.

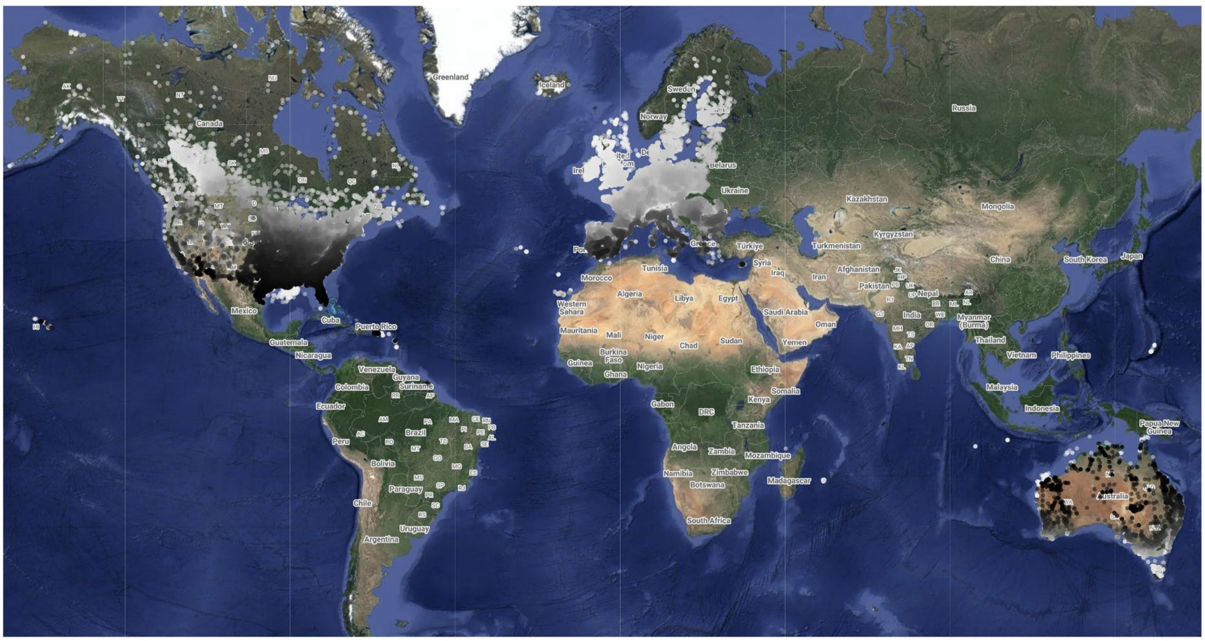

Fig. 7. Heat risk of industrial company sites in the sample in Cooling Degree Days. The map was created by the authors with Google Looker Studio, https://lookerstudio.google.com, Map data 2024 Google, Imagery 2024 NASA. The colour scale of the map starts with light gray (lowest heat risk in terms of cooling degree days) and ends with black (highest heat risk in terms of cooling degree days). 2019 observations have been used.

Received: 14 March 2024; Accepted: 5 December 2024
Published online: 07 January 2025

References

1. Bingler, J. A., Kraus, M., Leippold, M. & Webersinke, N. Cheap talk and cherry-picking: What ClimateBert has to say on corporate climate risk disclosures. *Finance Research Letters*. **47**, https://doi.org/10.1016/j.frl.2022.102776 (2022).
2. Principale, S. & Pizzi, S. The determinants of TCFD Reporting: A focus on the Italian context. *Administrative Sciences*. **13**, https://doi.org/10.3390/admsci13020061 (2023).
3. Sörme, L., Palm, V. & Finnveden, G. Using E-PRTR data on point source emissions to air and water-first steps towards a national chemical footprint. *Environmental Impact Assessment Review*. **56**, 102–112. https://doi.org/10.1016/j.eiar.2015.09.007 (2016).
4. DeVito, S. C., Keenan, C. & Lazarus, D. Can pollutant release and transfer registers (PRTRs) be used to assess implementation and effectiveness of green chemistry practices? A case study involving the toxics release inventory (TRI) and pharmaceutical manufacturers. *Green Chemistry*. **17**, 2679–2692. https://doi.org/10.1039/c5gc00056d (2015).
5. Strezov, V., Zhou, X. & Evans, T. J. Life cycle impact assessment of metal production industries in Australia. *Scientific Reports*. **11**, https://doi.org/10.1038/s41598-021-89567-9 (2021).
6. Erhart, S. & Erhart, K. Environmental ranking of European industrial facilities by toxicity and global warming potentials. *Nature Scientific Reports*. https://doi.org/10.1038/s41598-022-25750-w (2023).
7. Petrl, J. et al. *Pollutant Release and Transfer Register and Civil Society* (2023).
8. Nordborg, M. et al. Updated indicators of Swedish national human toxicity and ecotoxicity footprints using USEtox 2.01. *Environmental Impact Assessment Review*. **62**, 110–114. https://doi.org/10.1016/j.eiar.2016.08.004 (2017).
9. Erhart, S. & Erhart, K. Application of North European characterisation factors, population density and distance-to-coast grid data for refreshing the Swedish human toxicity and ecotoxicity footprint analysis. *Environmental Impact Assessment Review*. **92**, 106686. https://doi.org/10.1016/j.eiar.2021.106686 (2022).
10. Nguyen, H. T., Aviso, K. B., Fujioka, M., Ito, L. & Tokai, A. Decomposition analysis of annual toxicological footprint changes: Application on Japanese industrial sectors, 20012015. *Journal of Cleaner Production* **290**, 125681. https://doi.org/10.1016/j.jclepro.2020.125681 (2021).
11. Sala, S. & Goralczyk, M. Chemical footprint: A methodological framework for bridging life cycle assessment and planetary boundaries for chemical pollution. *Integrated Environmental Assessment and Management* **9**, 623–632. https://doi.org/10.1002/ieam.1471 (2013).
12. Lee, C.-C. et al. *How does the research community contribute to corporate climate-related risk disclosures?* (The gap between ideals and reality, Corporate Social Responsibility and Environmental Management, 2023).
13. Hain, L. I., Kölbel, J. F. & Leippold, M. Lets get physical: Comparing metrics of physical climate risk. *Finance Research Letters*. **46**, 102406. https://doi.org/10.1016/j.frl.2021.102406 (2022).
14. European Commission, New rules on corporate sustainability reporting: The Corporate Sustainability Reporting Directive (2023).
15. Task Force on Climate-related Financial Disclosures, Recommendations of the task force on climate-related financial disclosures (2017).
16. Simane, B. et al. Occupational heat stress in the floriculture industry of Ethiopia: Health risks and productivity losses. *Health*. **14**, https://doi.org/10.4236/health.2022.142020 (2022).
17. Bonafede, M. et al. Workers perception heat stress: Results from a pilot study conducted in Italy during the covid-19 pandemic in 2020. *International Journal of Environmental Research and Public Health* **19**, https://doi.org/10.3390/ijerph19138196 (2022).
18. Reboredo, J. C. & Ugolini, A. Climate transition risk, profitability and stock prices. *International Review of Financial Analysis*. **83**, https://doi.org/10.1016/j.irfa.2022.102271 (2022).
19. World Bank, Energy transition and universal access (2021).
20. Fatica, S., Katay, G. & Rancan, M. *Addressing physical climate risk: the case of flood protection*[SPACE]https://doi.org/10.1016/b978-0-44-313776-1.00020-9 (2023).
21. Holger, D. At least 10,000 foreign companies to be hit by EU sustainability rules. *Wall Street Journal* (2023).
22. OECD-JRC. Handbook on constructing composite indicators, methodology and user guide. (2008).
23. ICF. *Review of E-PRTR implementation and related guidance, Final Report* (2020).
24. Mistry, M. N. A high-resolution (0.25 degree) historical global gridded dataset of monthly and annual cooling and heating degree-days (1970–2018) based on GLDAS data, https://doi.org/10.1594/PANGAEA.903123. Supplement to: Mistry, MN (2019): Historical global gridded degree-days: A high-spatial resolution database of CDD and HDD. *Geoscience Data Journal*[SPACE]https://doi.org/10.1002/gdj3.83 (2019).
25. Dottori, F. et al. Development and evaluation of a framework for global flood hazard mapping. *Advances in Water Resources*[SPACE]https://doi.org/10.1016/j.advwatres.2016.05.002 (2015).
26. OECD. Guidance document on elements of a prtr: Part i. *"Series on Pollutant Release and Transfer Registers"* (2014).
27. Edwards, S. J. & Walker, T. R. An overview of Canadas National Pollutant Release Inventory program as a pollution control policy tool. *Journal of Environmental Planning and Management*. **63**, https://doi.org/10.1080/09640568.2019.1634525 (2020).

Author contributions

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, methodology, software, data curation, writing, original draft preparation, visualisation. K.E. participated in the conceptualization, background database construction and curation. S.E. participated in the conceptualization and formulation of research, analyzed and visualized the results and wrote the main manuscript text. All authors discussed the results and contributed to reviewing the manuscript. S. Sz. participated in the conceptualization and formulation of research, analyzed and visualized the results and wrote the main manuscript text. All authors discussed the results and contributed to reviewing the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to S.E.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.