

Article

Facility-Level Operational Greenhouse Gas Emissions in Natural- and Faux-Fur Enterprises: A Descriptive Case Study

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Abstract

This study provides enterprise-level evidence on the magnitude, source composition, and variability of operational greenhouse gas (GHG) emissions in natural- and faux-fur enterprises in Western Macedonia, Greece. The 2025 analysis comprises nine enterprises (five natural fur and four faux fur) with comparable inventories, drawn from a broader sample of 54 enterprises within an approximate regional frame of 200. The restricted facility indicator combines Scope 1 stationary heating-oil combustion and Scope 2 purchased electricity. Mean emissions were 4.982 and 6.110 t CO₂e per enterprise in the natural-fur and faux-fur groups, respectively, a descriptive difference of 18.46%. Heating oil was the dominant source in every enterprise, accounting for 65.64% and 68.53% of the respective group component totals. Observed dispersion was greater in the natural-fur group (sample SD 1.550 versus 0.582 t CO₂e). Including company-vehicle emissions yielded a difference of 18.83%, while leave-one-out differences ranged from 14.18% to 29.58%, indicating sensitivity of the magnitude to individual observations. The source profile identifies heating as a priority for facility energy audits. Because the subset is small, non-random, heterogeneous, and not normalized by activity, the findings do not support causal or sector-wide inference or a comparative product life-cycle assessment.

Keywords: greenhouse gas emissions; organizational inventory; facility energy; natural fur; faux fur; Scope 1; Scope 2; descriptive case study

1. Introduction

Environmental Context and Research Question

Reducing greenhouse gas emissions from textile and apparel activities requires attention to both supply-chain impacts and energy consumption at operating facilities [1,2]. Natural fur and faux fur are compared as alternative product systems, yet their environmental assessment also depends on the operational setting in which enterprises use energy. Stationary fuel combustion and purchased electricity are distinct inventory sources that can inform local emissions management [3,4]. Examining their contribution is therefore relevant to identifying operational priorities, alongside broader assessments of material production and product use.

Textile and fur life-cycle studies examine impacts associated with materials, processing, and other stages within a defined product system [5–8]. Such assessments answer a different question from an annual enterprise inventory: they do not directly describe the distribution of heating-oil and purchased-electricity emissions across the facilities examined here. A



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facility-level dataset can complement product evidence by documenting the sources and variation of operational emissions, although absolute enterprise totals cannot establish relative product performance without a common functional unit.

The present study asks how annual emissions from stationary heating-oil combustion and purchased electricity vary within and between the observed natural-fur and faux-fur enterprise groups. Its purpose is to describe the magnitude and composition of facility emissions and their variability, rather than to infer a material-specific environmental advantage.

2. Related Work

2.1. Organizational GHG Accounting and Comparability

The GHG Protocol Corporate Standard and ISO 14064-1 emphasize transparent organizational and operational boundaries, completeness, consistency, and reproducibility in greenhouse gas inventories [3,9]. Stationary combustion of heating oil in sources owned or controlled by an organization is reported as Scope 1, whereas emissions from the generation of purchased electricity are reported as Scope 2 [3,4,9]. Common standards improve inventory quality but do not, by themselves, make organizations comparable when scale, boundary choices, estimation methods, and activity structures differ.

Published research has highlighted the difficulty of harmonizing corporate carbon footprints. Klaaßen and Stoll showed that heterogeneity in reporting practices and scope coverage can impair comparability even when firms appear to report similar headline indicators [10]. Downie and Stubbs likewise demonstrated that emission-factor and boundary choices can materially affect reported corporate GHG outcomes [11]. The present study therefore treats common boundary definition as a necessary, but not sufficient, condition for comparison.

Green [12] situates the GHG Protocol within private climate governance, explaining how company-level accounting standards gained broad adoption. Methodological work also warns against equating a restricted operational footprint with a complete carbon footprint: Matthews et al. [13] highlight the importance of estimation boundaries, while Hertwich and Wood [14] document the importance of industrial supply-chain emissions using input–output analysis. These studies justify distinguishing the heating-and-electricity indicator from a value-chain assessment. They do not establish the magnitude or dominant sources of omitted emissions for the enterprises examined here.

2.2. Textile Life-Cycle Evidence and the Importance of System Boundaries

Textile environmental assessment literature repeatedly identifies system boundaries and functional units as decisive methodological choices. Peters et al. discuss carbon-footprinting applications across textile systems, while broader reviews show that burdens can arise at raw-material, manufacturing, energy, transport, use, reuse, recycling, and end-of-life stages [1,2,5–7,15]. The environmental profile of a textile product therefore cannot be inferred from one operational stage alone.

More detailed textile studies show why a material label alone is insufficient for benchmarking. Van der Velden et al. [16] compare fabrics made from several natural and synthetic fibres and examine the influence of yarn characteristics and processing parameters. Steinberger et al. [17] explicitly differentiate geographical production and use-phase conditions in a global textile-chain inventory. Together, these studies show that process configuration, location, and product-system assumptions need to be specified before environmental results can be compared.

Wang et al. [18] assess Chinese cotton shirts over their life cycle, accounting for material and energy contributions beyond a single operating facility. Payet [19] examines textile products and production routes serving the French market and identifies the significance

of production energy mixes. These assessments cannot be used as direct benchmarks for annual enterprise totals, but they identify variables that a future product-based assessment of fur-sector activities would need to document.

At the operational level, Hasanbeigi and Price [20] review energy use by textile process and distinguish process-specific efficiency opportunities from measures applicable across subsectors. Their description of a fragmented, heterogeneous industry supports separating building services from production processes. Accordingly, a heating-dominated facility inventory should not be assumed to represent the energy profile of a complete textile manufacturing chain.

This literature establishes the interpretive rule applied throughout the present study: annual t CO₂e per enterprise is an organizational activity indicator, not a product-performance metric. Without a common denominator such as kilograms of finished product, number of garments, square metres processed, or equivalent function, a facility-level comparison cannot legitimately be transformed into a claim about the relative life-cycle impacts of two product categories.

2.3. Fur, Faux Fur, and Adjacent Material Assessments

The CE Delft report by Bijleveld compares natural mink-fur and faux-fur products under alternative lifetime and maintenance scenarios [8]. It is grey literature commissioned by Bont voor Dieren, GAIA Belgium, and LAV, rather than a peer-reviewed journal article. Studies of leather processing likewise assess specific operations and material inputs using product-based functional units [21,22]. This evidence helps identify relevant processes and boundary choices, but it does not provide an equivalent annual comparison of the heating and electricity emissions of the enterprises studied here.

Bevilacqua et al. [23] extend product-based carbon accounting to a woollen-product supply chain and examine supplier and transport choices. Organizational evidence is also available: Aykaç Özen et al. [24] report an annual inventory for a denim-washing company that includes direct, energy-indirect, and non-energy-indirect emissions. Thus, the contribution of the present study is sector-specific facility evidence, not a claim that organizational textile carbon accounting is absent from the literature.

2.4. Energy Management and Emissions Reporting in Small Enterprises

The operational interpretation also requires attention to enterprise-level constraints. Trianni and Cagno [25] investigate barriers to energy efficiency in SMEs, while Sardanou [26] examines Greek industrial investment decisions and emphasizes differences in managerial needs and access to qualified personnel and information. These findings indicate that identifying a technically relevant intervention and implementing it are distinct tasks. They do not demonstrate that any specific barrier is present in the nine enterprises studied here.

Using German SME energy-audit data, Fleiter et al. [27] identify investment costs, capital availability, and audit quality as influences on the adoption of efficiency measures. Backlund et al. [28] further argue that continuous energy-management practices complement efficient technologies. This evidence supports an audit-based approach to operational mitigation rather than assigning uniform savings to a fur category.

Recent emissions-reporting research addresses the shortage of SME data. Phillpotts et al. [29] develop Scope 1 and 2 prediction models using financial transaction information and firm characteristics. Such models offer a route to screening where inventories are unavailable, but predicted emissions are not equivalent to verified consumption records. The present analysis retains reported inventory outputs and does not impute emissions for the other 45 enterprises.

Within this wider literature, the gap addressed in this study is the limited description of operational source composition and between-enterprise variability within a common facility inventory boundary for the two fur-sector groups in Western Macedonia. The objective is to compare 2025 heating-oil and purchased-electricity emissions in nine enterprises with available inventories. By retaining individual observations and examining sensitivity, this descriptive dataset can inform facility energy audits and specify the additional activity data required for a normalized comparison.

3. Methodology

3.1. Sample and Classification of Enterprises

The approximate regional sectoral frame comprised 200 fur-sector enterprises in Western Macedonia. The broader study sample included 54 enterprises, of which 30 were classified as natural fur and 24 as faux fur. No probability-sampling claim is made for either the broader sample or the analytic subset. The quantitative analysis was restricted to the nine enterprises (five natural fur and four faux fur) for which complete and mutually comparable 2025 organizational GHG inventories were available for both stationary heating-oil combustion and purchased electricity. Complete comparable inventories for the required sources were not available for the other 45 enterprises (25 natural fur and 20 faux fur), which were therefore excluded from the enterprise-level emission comparison. The reported percentages describe only this non-random, availability-based analytic subset rather than the wider 54-enterprise sample or the regional sector. Enterprises in the analytic subset are identified consistently as Enterprise 1 through Enterprise 9 to protect commercial confidentiality. In Table 1 is presented the sampling frame, broader study sample, and analytic subset for natural and faux fur.

Table 1. Sampling frame, broader study sample, and analytic subset.

Study Level	Natural Fur	Faux Fur	Total
Approximate regional sectoral frame	Not available	Not available	≈200
Broader study sample	30	24	54
Not included in quantitative comparison	25	20	45
Analytic subset with complete comparable inventories	5	4	9

Note: Category-specific counts were not available for the approximate sectoral frame. Of the 54 enterprises in the broader study sample, 45 were not included in the quantitative comparison because complete comparable inventories for both required facility energy sources were unavailable. All emission statistics reported in this manuscript are calculated only from the nine-enterprise analytic subset. Enterprise identifiers in that subset have been anonymized consistently.

3.2. Common Operational Boundaries

The principal comparative indicator retains the sources represented consistently across all individual inventories: (a) Scope 1 emissions from stationary combustion of heating oil and (b) Scope 2 emissions from purchased electricity. Potential fugitive refrigerant emissions are not quantified because no data documenting refrigerant loss were available. Raw-material sourcing, upstream production, outsourced processing, third-party transport, packaging, waste, consumer use, and end-of-life management fall outside this restricted facility indicator. The accounting categories follow the organizational logic of the GHG Protocol and ISO 14064-1 [3,4,9]; the comparison is not a product life-cycle assessment.

3.3. Exclusion of the Mobile Source from the Comparative Indicator

Company-vehicle fuel is retained in each complete organizational inventory because combustion in vehicles owned or operationally controlled by the enterprise is a Scope 1 source [3,9].

The principal comparative indicator has a narrower purpose. It describes the two facility energy sources recorded for every enterprise, rather than the complete organizational inventory. Vehicle exclusion is therefore an analytical boundary choice, not a statement that the emissions are negligible or outside corporate responsibility.

Heating oil and purchased electricity have a common facility function across the examined enterprises. Vehicle use may instead vary with customer and supplier geography, distribution arrangements, travel, outsourcing, vehicle characteristics, and administrative choices.

For this reason, the restricted indicator reduces the influence of mobility patterns that are not directly linked to facility energy use. It does not establish that the retained sources are intrinsically comparable across enterprises.

Important sources of heterogeneity remain after vehicle exclusion, including facility size, workforce, operating hours, activity volume, equipment, building performance, and energy efficiency. The restricted indicator therefore cannot isolate a causal effect of fur category.

Accordingly, the restricted facility indicator is presented as the principal descriptive analysis, and the complete organizational inventory, including vehicles, is presented as a robustness check. Neither analysis supports causal or sector-wide inference.

3.4. Calculation Equations

The comparative facility indicator is defined as the sum of Scope 1 emissions from stationary heating-oil combustion and Scope 2 emissions from purchased electricity. These were the two sources available on a common basis across all nine inventories in the analytic subset.

$$E_{i,comp} = E_{i,heating} + E_{i,electricity} \quad (1)$$

All emission quantities are expressed in t CO₂e. In Equation (1), *i* denotes the enterprise, *E_{i,comp}* the restricted comparative indicator, *E_{i,heating}* Scope 1 stationary heating-oil emissions, and *E_{i,electricity}* Scope 2 purchased-electricity emissions. Company-vehicle emissions are excluded from Equation (1) but retained in the complete-inventory robustness analysis.

This analytical boundary improves consistency across the available facility sources but does not normalize the results for enterprise scale or activity.

3.4.1. Heating-Oil Emissions

Heating-oil emission totals were transferred from the individual 2025 organizational inventories. Equations (2)–(5) document the computational structure applied in those inventories. The comparative dataset does not contain the numerical fuel density, net calorific value, gas-specific CO₂, CH₄, and N₂O emission factors, GWP set, reference years, or primary factor citations needed to reconstruct the values independently. The heating-oil results are therefore treated as reported inventory outputs rather than as independently recalculated estimates. The underlying inventory records will be made available by the authors on reasonable request, subject to applicable commercial-confidentiality restrictions.

$$m_{i,fuel}(t) = V_i(L) \times \rho(kg/L)/1000 \quad (2)$$

where *V_i* is the recorded volume of heating oil for enterprise *i* and *ρ* is the fuel density used in the source inventory. Division by 1000 converts kilograms to metric tonnes.

$$A_i(TJ) = m_{i,fuel}(t) \times NCV(TJ/t) \quad (3)$$

where A_i is the energy activity in terajoules and NCV is the net calorific value of heating oil. Use of a common net calorific value keeps the energy basis of the calculation consistent across enterprises.

Emissions from heating-oil combustion are not limited to carbon dioxide. CO_2 , CH_4 , and N_2O are calculated separately because each gas has a different emission factor and contributes differently to total climate impact. For each gas g , the general relationship is:

$$E_{i,g} \text{ (t CO}_2\text{e)} = A_i \text{ (TJ)} \times EF_g \text{ (kg/TJ)} \times GWP_g/1000 \quad (4)$$

In Equation (4), EF_g is the emission factor for gas g and GWP_g is the corresponding global-warming potential, with CO_2 as the reference gas. Division by 1000 converts kilograms of CO_2 equivalent to tonnes. The total heating component is the sum of the individual gases:

$$E_{i,\text{heating}} = E_{i,\text{CO}_2} + E_{i,\text{CH}_4} + E_{i,\text{N}_2\text{O}} \quad (5)$$

CO_2 is expected to dominate heating-oil combustion emissions, while CH_4 and N_2O are included in the computational structure reported by the source inventories. Because the factor metadata were not retained in the comparative dataset, no alternative emission-factor or GWP set was imposed retrospectively. This avoids introducing assumptions that could be inconsistent with the original inventories, but it leaves the initial source-to-emission calculations only partially reproducible.

3.4.2. Purchased-Electricity Emissions

All inventories consistently apply an electricity emission factor of 0.274761 kg $\text{CO}_2\text{e/kWh}$. This value was carried forward from the individual source inventories. Its original publication, reference year, geographic basis, and classification as location-based or market-based were not preserved in the comparative dataset and could not be verified independently. The manuscript therefore does not assign either Scope 2 classification to the factor. The reported electricity totals should be interpreted as calculations made with a common inherited factor, which improves internal consistency across the nine enterprises but limits external reproducibility and comparison under the GHG Protocol Scope 2 Guidance [4].

$$E_{i,\text{electricity}} \text{ (t CO}_2\text{e)} = C_i \text{ (kWh)} \times 0.274761 \text{ (kg CO}_2\text{e/kWh)} / 1000 \quad (6)$$

In Equation (6), C_i is annual electricity consumption for enterprise i . Multiplication produces kg CO_2e , which is converted to t CO_2e by division by 1000.

3.4.3. Overall Composition and Consistency Checks

The supplied enterprise-level emission outputs were checked for consistent units, arithmetic agreement of component totals, and use of the common electricity factor. Enterprise-level activity data—annual litres of heating oil and kWh of purchased electricity—are not reproduced in the manuscript because they form part of the underlying company inventory records. As specified in the Data Availability Statement, these records will be made available by the authors on reasonable request, subject to applicable commercial-confidentiality restrictions. Table 2 and Appendix A permit reproduction of the reported group aggregations, but independent reconstruction of every source-to-emission calculation additionally requires access to those records and the original factor metadata.

Table 2. Enterprise-level 2025 emissions used in the comparison.

Enterprise	Group	Heating Oil, Scope 1 (t CO ₂ e)	Purchased Electricity, Scope 2 (t CO ₂ e)	Restricted Facility Total (t CO ₂ e)	Company Vehicles, Scope 1 * (t CO ₂ e)
1	Natural fur	5.143	2.555	7.698	1.581
2	Natural fur	3.165	1.594	4.759	1.476
3	Natural fur	2.901	1.511	4.412	1.792
4	Natural fur	2.506	1.429	3.934	1.265
5	Natural fur	2.638	1.470	4.107	1.581
6	Faux fur	4.748	2.061	6.808	2.108
7	Faux fur	4.352	1.978	6.330	1.897
8	Faux fur	3.693	1.786	5.478	2.003
9	Faux fur	3.956	1.868	5.825	1.686

* Vehicle emissions are included for reconciliation and robustness analysis but excluded from the principal facility indicator. Components and totals are displayed to three decimal places; apparent differences of 0.001 t CO₂e arise because totals were calculated from unrounded values. Source: processing of the nine supplied 2025 inventories in the analytic subset.

Calculations are performed without intermediate rounding to the extent technically possible. Rounding is applied at the final presentation stage to avoid cumulative deviations in sums and descriptive statistics. The displayed precision is kept consistent across tables, figures, and the main text.

For each group, the contribution of an emission source is calculated as 100 times the sum of that source across the enterprises divided by the sum of heating-oil and purchased-electricity emissions across the same enterprises. These are shares of the aggregated component emissions, not unweighted averages of enterprise percentages or shares of energy consumption. The new source shares are calculated from the component values displayed in Table 2 and rounded to two decimal places; minor differences from the reported facility totals reflect the original three-decimal presentation.

3.5. Statistical Approach

The statistical treatment is descriptive and exploratory. Its purpose is not to prove a causal relationship between fur category and operational emissions, but to organize the observed values in the nine-enterprise analytic subset consistently, describe their central tendency and dispersion, and support a cautious comparison of the two enterprise groups. This distinction is fundamental because the analytic subset is small, non-random, and composed of enterprises with different operational and organizational characteristics.

3.5.1. Descriptive Statistical Measures

For each group, the analysis presents the number of observations, the sum of comparative emissions, the arithmetic mean, the median, the sample standard deviation, the minimum, and the maximum. These measures are complementary: the mean expresses the average arithmetic burden, the median identifies the centre of the distribution with less sensitivity to extreme observations, and the standard deviation and range indicate within-group heterogeneity.

$$S = \sum E_{i,comp} \quad (7)$$

where S is the sum of comparative emissions for the group.

$$E_{avg} = (1/n) \times \sum E_{i,comp} \quad (8)$$

where E_{avg} is the arithmetic mean.

$$s = \sqrt{[\sum (E_{i,comp} - E_{avg})^2 / (n - 1)]} \quad (9)$$

where s is the sample standard deviation.

The median is calculated after observations are sorted in ascending order. When n is odd, it equals the middle observation; when n is even, it equals the arithmetic mean of the two central observations. The minimum and maximum define the observed endpoints, while the range can be expressed as the difference between the maximum and minimum.

$$R = E_{\max} - E_{\min} \quad (10)$$

The standard deviation is calculated as a sample standard deviation with denominator $n - 1$. This is consistent with treating the available enterprises as a limited set of observations rather than a complete census of the entire sector. Because each group contains very few units, however, the standard deviation must be read as a descriptive indicator of dispersion rather than a stable estimate of population variability.

3.5.2. Emphasis on the Median and Distribution of Values

The median and individual observations are considered alongside the arithmetic mean because each enterprise can materially affect a group with five or four observations. Absolute annual emissions are not normalized by workforce, production output, heated floor area, operating hours, or economic value added because no common, sufficiently documented activity dataset is available for all enterprises. Reported headcounts alone do not account for differences in output, operating schedules, or the space being heated. Normalization is therefore not approximated using assumed activity levels.

The median, range, and individual observations are therefore reported alongside the mean. A leave-one-out analysis removes each enterprise in turn and recalculates the comparison, providing a symmetric assessment of sensitivity rather than focusing on a single selected observation.

3.5.3. Non-Application of Inferential Significance Tests

No statistical significance tests are conducted, and no p -values are calculated for the difference between the two groups. This is a deliberate methodological decision rather than an omission. The conditions for a reliable inferential comparison are not adequately met: the number of observations is limited, the enterprises were not selected by random sampling, the groups are small and unequal, and neither a common distribution nor homogeneity of variances is established. Under these conditions, a conventional significance test could produce a numerical result with an unjustifiably strong appearance of certainty.

Moreover, statistical association would not constitute causal proof. Fur category coexists with other determinants, including enterprise size, workforce, facility area, operating hours, equipment technology, building energy efficiency, and activity volume. Because these factors are not available in a common and sufficiently documented form for all enterprises, the independent effect of fur category on emissions cannot be isolated.

3.5.4. Limits to Generalization and Appropriate Use of the Results

The results concern only the nine-enterprise analytic subset and the study reporting period. They cannot automatically be generalized to the broader sample of 54 enterprises, to the approximate regional frame of 200 enterprises, or to the natural-fur or faux-fur sector as a whole; nor do they represent a complete environmental assessment of the corresponding products. The analysis is restricted to common facility operational emissions from heating and electricity and does not constitute a product LCA.

The group sum and mean are useful for describing this sample but are not used as stand-alone criteria of environmental superiority. Particular weight is given to the median, the distribution, the range, and inspection of the individual enterprises. This keeps the

statistical treatment proportionate to the quality and extent of the available data and avoids conclusions that exceed their actual evidential content.

A more complete future comparison would require the collection of common activity indicators and the normalization of emissions, for example per employee, per square metre of facility, per operating hour, or per unit of product. A larger and more representative sample could also support multivariable analysis, control for confounding factors, and, under appropriate conditions, inferential testing. At the present stage, a descriptive approach is the scientifically cautious and transparent choice.

4. Results and Discussion

4.1. Data and Results by Enterprise

Table 2 reports the enterprise-level 2025 emission outputs. Heating oil and purchased electricity constitute the restricted facility indicator, while the vehicle column permits reconciliation with the broader reported organizational inventories. The table supports reproduction of the group aggregations; reconstruction of the underlying source calculations additionally requires the activity records and factor metadata described in Section 3.4. In Figure 1 it is presented the Restricted facility operational emissions by anonymized enterprise.

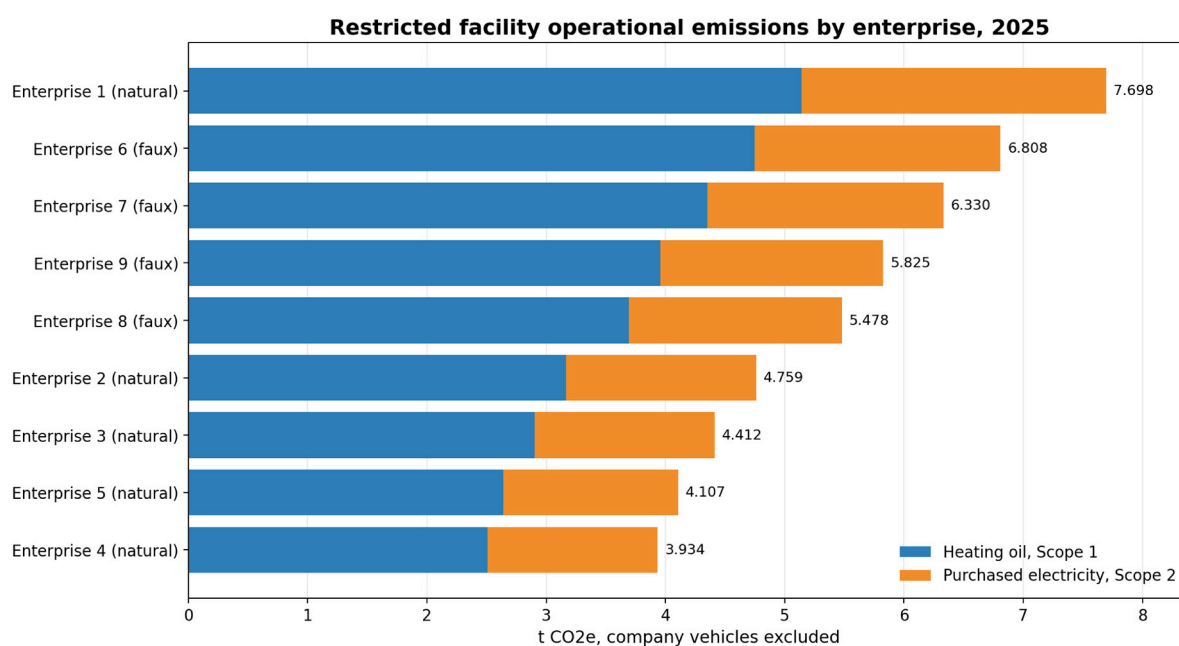


Figure 1. Restricted facility operational emissions by anonymized enterprise. Bars show Scope 1 stationary heating-oil emissions and Scope 2 purchased-electricity emissions; company-vehicle emissions are excluded.

4.2. Aggregated Statistics by Group

The restricted facility mean was 18.46% lower in the natural-fur group. Table 3 and Figure 2 also show lower observed dispersion in the four faux-fur enterprises, whereas the natural-fur distribution includes a higher-valued observation. These patterns describe the analytic subset and do not establish group differences in operational efficiency or population variability.

Table 3. Descriptive statistics and source shares by group.

Indicator	Natural Fur	Faux Fur
Number of enterprises	5	4
Sum (t CO ₂ e)	24.911	24.442
Mean (t CO ₂ e per enterprise)	4.982	6.110
Median (t CO ₂ e)	4.412	6.077
Sample standard deviation (t CO ₂ e)	1.550	0.582
Minimum (t CO ₂ e)	3.934	5.478
Maximum (t CO ₂ e)	7.698	6.808
Heating-oil share of component emissions (%)	65.64	68.53
Purchased-electricity share of component emissions (%)	34.36	31.47

Source: reported descriptive statistics for the restricted facility totals, with vehicle emissions excluded. Source shares are ratios of summed heating-oil and electricity components in Table 2, calculated from the displayed values and rounded to two decimal places. They represent emission shares, not energy shares. In Figure 2, is presented the distribution of the restricted facility indicator by group.

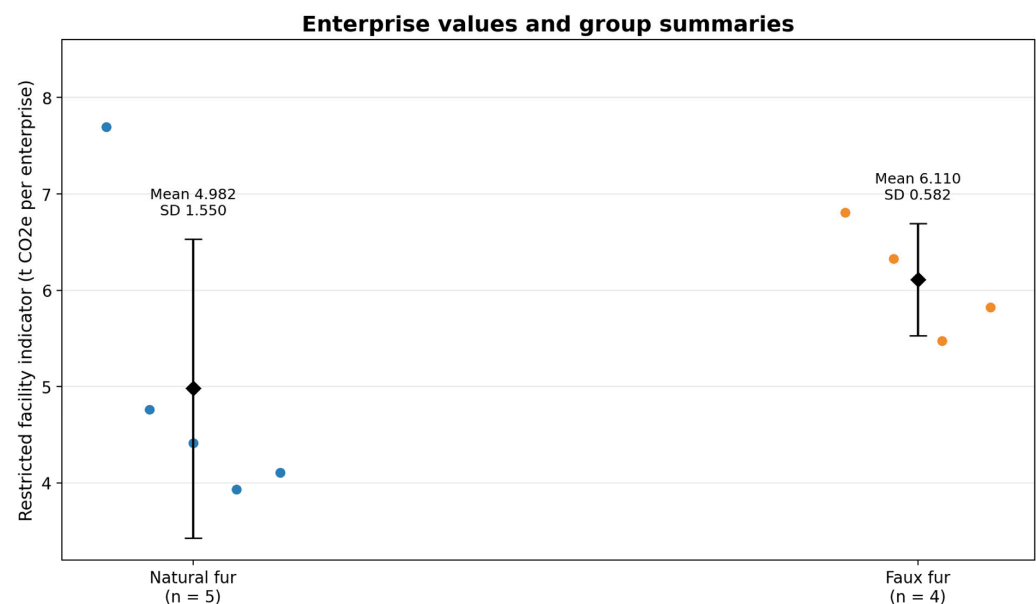


Figure 2. Distribution of the restricted facility indicator by group. Points represent enterprises, diamonds represent group means, and error bars represent one sample standard deviation.

4.3. Emission Source Composition and Operational Implications

Summing the displayed components in Table 2 gives 16.353 t CO₂e from heating oil and 8.559 t CO₂e from electricity in the natural-fur group, corresponding to 65.64% and 34.36% of its component total. The faux-fur group records 16.749 and 7.693 t CO₂e, respectively, corresponding to 68.53% and 31.47%. Heating oil is the larger source in every enterprise. Both groups therefore share a heating-dominated emission profile within the restricted boundary, despite differences in their mean totals.

Regional heating demand provides a plausible context for this pattern. Karakosta and Vryzidis [30] documented high heating needs and the relevance of envelope and heating-system performance in school buildings in Western Macedonia. These findings concern a different building use and cannot be transferred quantitatively to fur-sector facilities. They nevertheless support considering winter conditions, insulation, heated floor area, and boiler performance when interpreting fuel use. Papakostas et al. [31] similarly use degree-day analysis to examine temperature-related heating and cooling demand in Greek residential buildings. Although neither study measures the facilities examined here,

both provide a rationale for collecting local climatic and building-use information before attributing fuel differences to enterprise category.

In small operations, heating an occupied workspace may generate a facility load that is not proportional to production output. Operating schedules, thermostat settings, and heat losses could therefore affect the reported heating component independently of fur category. These are plausible explanations, not demonstrated causes: the dataset contains neither building energy audits nor monthly demand profiles nor enterprise-specific heating degree days that would permit attribution.

The emission shares identify heating as a priority for further facility assessment, rather than demonstrating the effectiveness of a particular intervention. Audits could evaluate envelope improvements, heating controls, and alternative heat supply alongside electrical equipment and lighting. The potential savings and appropriate technology would depend on facility-specific conditions and the carbon intensity of replacement energy sources [1,30]. Evidence on SME audit quality and continuous energy management [27,28] also supports evaluating implementation conditions alongside technical options. No intervention-specific savings are estimated from the present dataset.

4.4. Enterprise Scale and Interpretation of Enterprise 1

Enterprise 1 has the highest restricted facility total (7.698 t CO₂e) and a reported workforce of five persons, whereas the remaining enterprises were described as single-person operations. Its position above the other natural-fur observations contributes to the greater observed dispersion in that group. The coincidence of higher emissions and a larger workforce does not establish workforce as the cause of the difference.

Without common measures of production output, workforce activity, heated floor area, and operating hours, the higher total cannot distinguish a larger scale of operation from greater energy intensity. A per-employee indicator would describe emissions relative to staffing, while a per-unit-output indicator would address production intensity; neither is interchangeable with a floor-area or operating-hour denominator. The available headcount is therefore insufficient for a defensible adjusted comparison. Enterprise 1 is retained as an observed case, and its numerical influence is evaluated symmetrically with that of every other enterprise in Section 4.5.

4.5. Robustness and Leave-One-out Sensitivity Analyses

Retaining company-vehicle emissions gives mean reported organizational inventories of 6.521 t CO₂e for natural-fur enterprises and 8.034 t CO₂e for faux-fur enterprises, a descriptive difference of 18.83%. Vehicle exclusion therefore does not determine the direction of the observed comparison. In the leave-one-out analysis, each enterprise was removed in turn while the other group remained unchanged. The natural-fur mean remained lower in every iteration, but the difference ranged from 14.18% after removal of Enterprise 4 to 29.58% after removal of Enterprise 1. Figure 3, illustrates leave-one-out sensitivity of the percentage difference between group means for the restricted facility indicator.

The leave-one-out range spans 15.40 percentage points. Removing the highest natural-fur observation enlarges the difference, whereas removing the lowest natural-fur observation narrows it. Thus, directional stability coexists with substantial sensitivity of the magnitude: the reported 18.46% is not a stable estimate of a sectoral or material-specific effect. The range describes deterministic recalculations of this dataset, not a confidence interval. Neither check resolves confounding, selection bias, or the absence of activity normalization.

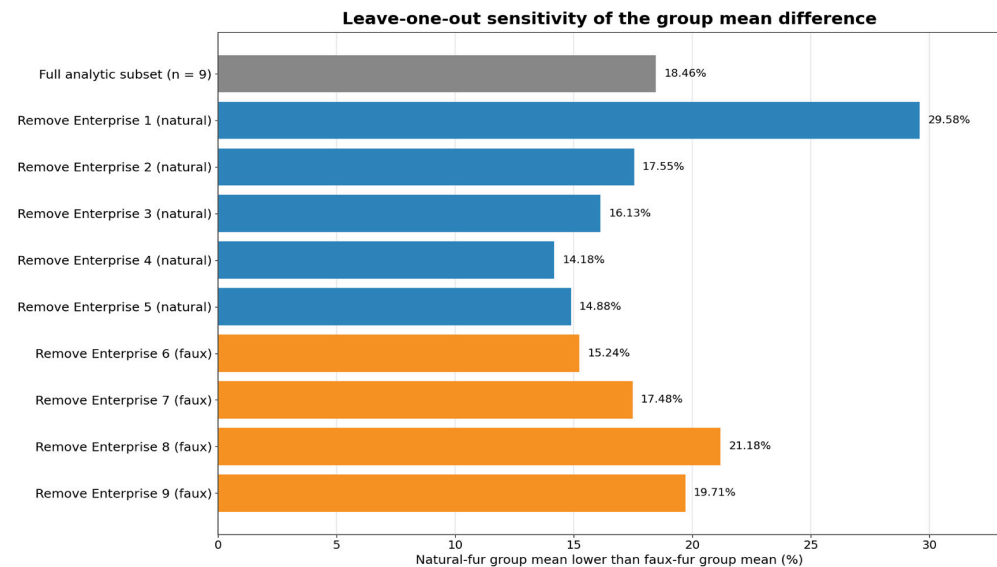


Figure 3. Leave-one-out sensitivity of the percentage difference between group means for the restricted facility indicator. Positive values indicate that the natural-fur group mean is lower than the faux-fur group mean.

4.6. Comparison with Previous Evidence

The prominence of energy-related emissions is conceptually consistent with the textile literature, which identifies energy supply and production processes as important contributors to environmental impacts [1,5]. Gonzalez et al. [7] compared six natural and synthetic fibres across material production, spinning, weaving, and dyeing and found that the distribution of impacts varies by fibre and processing stage. The heating-dominated profile observed here concerns a much narrower operational boundary. It complements this process-level evidence but cannot characterize the energy profile of complete textile or fur production systems, including upstream material manufacture.

The closer organizational comparison is the denim-washing inventory of Aykaç Özen et al. [24], in which natural-gas heating and purchased electricity contributed 62.67% and 32.15% of the annual footprint, respectively. This is qualitatively consistent with the prominence of heating observed here. However, that inventory includes additional sources, uses a different heating fuel, and concerns different operations. Its percentages therefore provide contextual evidence, not a like-for-like efficiency benchmark or validation of a natural-fur versus faux-fur effect.

Product-level evidence can identify a different dominant stage. In the scenario-based cotton T-shirt LCA of Feichtinger et al. [32], fabric manufacturing accounts for approximately 73% of climate-change impacts on average, with energy-intensive dyeing an important contributor. That result concerns a product system and functional unit, not annual building heating. Together with the process and location differences reported in textile studies [16,17,19,20], it reinforces the need to distinguish operational source shares from life-cycle contribution analyses.

Adjacent leather studies further show that the apparent dominant contributors depend on the processes and impact categories included. Tasca and Puccini [21] identified power-supply emissions as important contributors to several environmental impact categories in retanning, fatliquoring, and dyeing. Yu et al. [22] identified the tanning operation as the main contributor to the impacts of the tanning systems they assessed. These results are not evidence that heating oil should dominate all leather or fur inventories. Rather, they illustrate why a facility heating-and-electricity indicator and a broader process assessment can identify different priorities.

The absolute annual totals in this study cannot be quantitatively benchmarked against product-based LCA results without equivalent activity denominators and system boundaries. The CE Delft fur comparison [8], for example, evaluates product scenarios rather than annual enterprise totals. Likewise, a product-based impact expressed per unit of fibre or leather is not directly comparable to t CO₂e per enterprise. The present results therefore neither confirm nor contradict a product-level ranking of natural and faux fur. Their value is in locating operational emission sources and documenting variability that a future normalized dataset would need to explain.

This interpretation also accords with the corporate-accounting evidence discussed by Klaaßen and Stoll [10]: consistent reporting boundaries are important for comparisons, but they do not make entities with different activities equivalent. Here, the similar source composition across groups supports a shared focus on facility heating, while the differences in absolute totals remain inseparable from unmeasured enterprise characteristics.

The SME reporting work of Phillpotts et al. [29] also illustrates why enterprise characteristics matter when interpreting Scope 1 and 2 emissions. The absence of common financial, production, area, and operating-time data here prevents either an adjusted comparison or defensible extrapolation to the broader sample. Consequently, extending the quantitative comparison to the broader sample would require additional verified activity and enterprise-characterization data.

4.7. Limitations and Scope of Interpretation

The quantitative comparison relies on a small, non-random, availability-based subset of nine enterprises from the broader sample of 54. Selection according to inventory availability may favour enterprises with more complete records, and common data on output, floor area, operating hours, equipment, and energy efficiency are lacking. Harmonized accounting categories do not resolve these differences [10,11]. The observed distributions and percentage differences therefore cannot be generalized to the broader sample, the approximate regional frame of 200 enterprises, or either fur sector.

The restricted indicator omits upstream materials, outsourced processing, third-party transport, packaging, waste, use-phase duration, repair, reuse, and end-of-life. It also does not quantify all environmental impact categories or fugitive refrigerant losses. Consistent with product LCA literature [5,6,8,15], it should be interpreted as an operational inventory indicator rather than a measure of overall product sustainability. Greater absolute facility emissions need not imply poorer environmental performance per unit of output.

Finally, the numerical provenance of the original heating-oil factors and the reference year, geographic basis, and location-based or market-based classification of the electricity factor were not preserved in the comparative dataset. The enterprise outputs support reproduction of the descriptive summaries and source shares, but complete independent reconstruction of the initial source-to-emission calculations requires the underlying records and factor metadata. This limitation affects external comparability even though a common inherited factor was used within the available electricity inventories.

5. Conclusions

Within the 2025 analytic subset, the restricted facility mean was lower for natural-fur than for faux-fur enterprises (4.982 versus 6.110 t CO₂e per enterprise), with greater observed dispersion. Heating oil contributed 65.64% and 68.53% of the respective group component totals and was the largest source in every enterprise. Inclusion of vehicles preserved the direction of the group comparison, but the leave-one-out range of 14.18% to 29.58% demonstrates sensitivity in its magnitude.

The principal practical implication is to prioritize assessment of heating demand and heat supply when investigating operational mitigation in these facilities. This is an audit priority, not a quantified prediction of savings or evidence of a fur-category advantage. The small non-random subset, absence of activity normalization, restricted inventory boundary, and incomplete factor metadata limit the findings to a descriptive facility-level comparison.

Future work should collect verified heating-oil and electricity activity data with complete factor provenance, common output measures, workforce activity, heated floor area, operating hours, and heating degree days. Separating building services from production processes would enable interpretation of the heating-dominated profile. A larger, systematically selected dataset could support adjusted comparisons, while product-level assessment would additionally require material inputs, outsourced processes, transport, and use and end-of-life scenarios under a common functional unit.

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Data Availability Statement: The enterprise-level activity data supporting the analysis (including annual heating-oil consumption in litres, purchased-electricity consumption in kWh, and the corresponding source inventory records for the nine enterprises in the analytic subset) are available through a controlled-access procedure. Requests should be sent to the corresponding author at dziouzios@uowm.gr and will be evaluated subject to the confidentiality commitments and permissions applicable to the participating enterprises. The emission outputs and arithmetic aggregations used in the manuscript are reported in Table 2 and Appendix A.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Reconciliation with the Complete Organizational Inventories

The complete organizational inventory equals the restricted facility indicator plus company-vehicle emissions. These values also support the complete-inventory robustness analysis in Section 4.5.

Table A1. Arithmetic check: complete organizational inventory minus vehicle emissions equals the restricted facility indicator.

Enterprise	Complete Organizational Inventory (t CO ₂ e)	Minus Vehicle Emissions (t CO ₂ e)	Restricted Facility Indicator (t CO ₂ e)
1	9.279	1.581	7.698
2	6.234	1.476	4.759
3	6.204	1.792	4.412
4	5.199	1.265	3.934
5	5.688	1.581	4.107
6	8.916	2.108	6.808
7	8.227	1.897	6.330
8	7.481	2.003	5.478
9	7.511	1.686	5.825

Source: arithmetic reconciliation reported in the supplied study. Values are displayed to three decimal places; apparent differences of 0.001 t CO₂e arise because reconciled totals were calculated from unrounded values.

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