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A Primary-Data Scope 3 Carbon and Water Footprint Inventory of the Bangladesh Ready-Made Garment Sector: Modelling Export Exposure Under the European Union Carbon Border Adjustment Mechanism

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Research Article

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A Primary-Data Scope 3 Carbon and Water Footprint Inventory of the Bangladesh Ready-Made Garment Sector: Modelling Export Exposure Under the European Union Carbon Border Adjustment Mechanism

Abstract

The European Union's Carbon Border Adjustment Mechanism (CBAM) entered its definitive, financially binding phase on 1 January 2026, and the European Commission has signalled its intention to extend the mechanism's scope toward downstream and chemical-intensive products over the present decade, placing the ready-made garment (RMG) sector within its medium-term reach. For Bangladesh, where apparel accounts for more than four-fifths of merchandise exports and the EU absorbs more than half of those apparel shipments, the prospective inclusion of garments under CBAM represents a material threat to export competitiveness, compounded by the country's imminent graduation from least-developed-country status in November 2026 and the consequent erosion of preferential market access. Yet the empirical basis for quantifying this exposure is weak: Bangladesh lacks a sector-specific, primary-data greenhouse-gas and water-footprint inventory for its textile and RMG industries, and existing national inventories treat these industries as an undifferentiated subset of manufacturing using top-down methods. This study addresses that gap by constructing a primary-data carbon and water footprint inventory of the Bangladesh RMG sector, structured according to the Greenhouse Gas Protocol scope taxonomy, and by coupling the inventory to a scenario model of CBAM export exposure. Facility-level activity data were assembled for thirty-two representative manufacturing units spanning knit, woven and denim product lines, and characterised against the cradle-to-gate system boundary. The inventory yields a sector-weighted mean cradle-to-gate global warming potential of 16.0 kg CO_2-equivalent per kilogram of finished garment, of which Scope 3 upstream activities (principally fibre and yarn production) contribute approximately forty-two per cent, Scope 2 grid electricity twenty-seven per cent, Scope 1 onsite combustion and effluent treatment twenty-five per cent, and Scope 3 downstream export freight six per cent. The mean blue-water footprint of wet processing is 136 litres per kilogram and the grey-water footprint 119 litres per kilogram, consistent with independent Bangladeshi field studies. A Monte Carlo analysis over primary-data input ranges returns a 90 % credible interval of 12.4 to 20.1 kg CO_2-eq per kilogram. The CBAM exposure model indicates that, at a reference certificate price of EUR 100 per tonne CO_2 and under the Scope 1+2 accounting boundary, the embedded-carbon liability is approximately EUR 0.95 per kilogram of garment, equivalent to an ad-valorem exposure of approximately 4.8 per cent of free-on-board export value under business-as-usual conditions. A modelled

decarbonisation pathway combining energy efficiency, rooftop photovoltaics, renewable power-purchase agreements, process-heat electrification, low-impact dyeing and recycled-fibre substitution reduces the cradle-to-gate footprint by approximately fifty-four per cent and the ad-valorem CBAM exposure to approximately 1.3 per cent. The study provides the first integrated, primary-data, scope-resolved carbon and water inventory of the Bangladesh RMG sector tied explicitly to CBAM exposure modelling, and offers an evidence base for sector decarbonisation strategy, buyer engagement and trade-policy negotiation.

Keywords: carbon footprint; water footprint; ready-made garment; Bangladesh; Scope 3; Carbon Border Adjustment Mechanism; CBAM; life cycle inventory; export competitiveness; textile sustainability

Abbreviations: BGMEA – Bangladesh Garment Manufacturers and Exporters Association; CBAM – Carbon Border Adjustment Mechanism; CO_2-eq – carbon dioxide equivalent; ETP – effluent treatment plant; ETS – Emissions Trading System; EU – European Union; FOB – free on board; GHG – greenhouse gas; GWP – global warming potential; LCA – life cycle assessment; LCI – life cycle inventory; LDC – least developed country; PC – polyester-cotton; PES – polyester; PPA – power purchase agreement; PV – photovoltaic; RMG – ready-made garment; WF – water footprint; ZDHC – Zero Discharge of Hazardous Chemicals.

1. Introduction

1.1 The Bangladesh ready-made garment sector and its export dependence

The ready-made garment (RMG) sector is the cornerstone of the Bangladesh economy. The sector generates more than four-fifths of the country's merchandise export earnings, directly employs several million workers (a majority of them women from rural households), and has propelled Bangladesh to the position of the world's second-largest apparel exporter after China. The European Union is the single most important destination for these exports, absorbing more than half of Bangladesh's global apparel shipments, with the EU market valued at approximately nineteen to twenty billion US dollars in recent fiscal years. The sector's competitiveness has historically rested on a combination of low labour costs, preferential duty-free market access under the EU's least-developed-country (LDC) trade facility, and a deep and increasingly vertically integrated domestic manufacturing base spanning spinning, knitting, weaving, wet processing and garment assembly.

This export dependence renders the sector acutely sensitive to changes in the regulatory and tariff environment of its principal market. Two such changes are converging over the present decade. The first is Bangladesh's scheduled graduation from LDC status in November 2026, after which preferential duty-free access to the EU will continue only for a transitional period before reverting, absent a successor arrangement, to standard most-favoured-nation tariffs estimated at approximately twelve per cent on apparel. The second is the entry into force of the EU's Carbon Border Adjustment Mechanism (CBAM), whose definitive and financially binding phase commenced on 1 January 2026 and whose scope the European Commission has signalled an intention to extend toward downstream and chemical-intensive products, bringing apparel within its medium-term reach.

1.2 The Carbon Border Adjustment Mechanism

The CBAM is the European Union's instrument for addressing carbon leakage, the phenomenon whereby carbon-intensive production migrates from jurisdictions with stringent carbon pricing to jurisdictions with weaker constraints. The mechanism attaches to imports of covered goods a carbon cost mirroring the price that European producers pay under the EU Emissions Trading System (ETS), thereby equalising the carbon cost of imported and domestically produced goods.

In its initial definitive-phase scope, CBAM covers cement, iron and steel, aluminium, fertilisers, electricity and hydrogen; importers of these goods must report embedded emissions and surrender CBAM certificates priced against the ETS allowance price.

The Commission has been explicit that the initial scope represents a first step rather than an end state. A legislative proposal published in December 2025 set out the extension of the mechanism toward steel- and aluminium-intensive downstream products from 2028, and the Commission's review communications have identified chemicals and polymers, including the polyester and polyamide that constitute the synthetic backbone of modern apparel supply chains, as candidate sectors for inclusion by the end of the decade. While garments are not within the current covered-goods list, the trajectory of the mechanism and the policy emphasis on closing downstream and circumvention loopholes mean that the RMG sector must treat CBAM exposure as a foreseeable rather than a hypothetical risk.

Independent analyses have begun to quantify the potential exposure. A study by the Centre for Policy Dialogue estimated that, were apparel to be brought within the CBAM methodology at prevailing Bangladeshi emission intensities, the carbon cost would amount to approximately 4.8 per cent of export value, which, combined with the loss of LDC preferences and the application of the standard most-favoured-nation duty, could raise the total effective tariff on Bangladeshi apparel entering the EU to nearly seventeen per cent. Other analyses have warned that Bangladesh risks losing up to thirty per cent of its EU garment exports if it fails to close the gap between its current emission intensity and the decarbonisation trajectory of its principal competitors. The salience of this exposure is heightened by Bangladesh's comparatively low renewable-energy share in electricity generation, reported at approximately 5.4 per cent, well behind competitors such as India, Vietnam, Pakistan and Cambodia.

1.3 The primary-data inventory gap

The capacity of the Bangladesh RMG sector to respond to CBAM exposure is constrained at the most basic level by the absence of a robust, sector-specific, primary-data greenhouse-gas and water-footprint inventory. National and international emission inventories that cover Bangladesh typically treat textiles and RMG as an undifferentiated subset of the national manufacturing sector, characterised by top-down apportionment of aggregate energy and emission statistics rather than

by bottom-up measurement of facility-level activity. Where sector-specific studies exist, they tend to focus narrowly on energy efficiency or on water consumption in isolation, rather than on an integrated, scope-resolved carbon-and-water inventory tied to the regulatory accounting boundaries that CBAM will impose.

This gap matters because CBAM compliance, and indeed any credible decarbonisation strategy, requires emission data resolved at the level of the installation and the product, classified according to the Greenhouse Gas Protocol scope taxonomy (Scope 1 direct emissions, Scope 2 purchased-energy emissions, Scope 3 value-chain emissions), and accompanied by a defensible quantification of uncertainty. Absent such data, Bangladeshi exporters cannot accurately estimate their prospective CBAM liability, cannot identify the abatement measures that would most efficiently reduce it, and cannot substantiate to EU buyers or to the CBAM registry the embedded-emission values on which their market access will depend. The reliance on default values, which the CBAM methodology applies in the absence of verified primary data and which are typically set conservatively high, would impose a systematic penalty on exporters unable to demonstrate their actual, and frequently lower, emission intensity.

1.4 Research objectives and contributions

This study addresses the inventory gap by constructing a primary-data carbon and water footprint inventory of the Bangladesh RMG sector and coupling it to a scenario model of CBAM export exposure. The study pursues four objectives: to compile a facility-level, primary-data activity inventory for a representative sample of Bangladeshi RMG manufacturing units; to characterise the cradle-to-gate carbon footprint of representative garment products, resolved by Greenhouse Gas Protocol scope; to quantify the blue, green and grey water footprint of the wet-processing stage from primary data; and to model the prospective CBAM export exposure of the sector under a range of carbon-price and decarbonisation scenarios.

The contributions are threefold. First, the study provides, to the author's knowledge, the first integrated, primary-data, scope-resolved carbon-and-water inventory of the Bangladesh RMG sector that is explicitly structured to align with the CBAM accounting boundary. Second, it couples this inventory to an export-exposure model that translates physical emission intensity into ad-valorem trade-cost terms, providing a directly policy-relevant metric. Third, it evaluates a marginal

decarbonisation pathway that quantifies the carbon-footprint and CBAM-exposure reductions achievable through a sequence of feasible abatement measures, providing an evidence base for sector strategy, buyer engagement and trade-policy negotiation. The remainder of the article is organised as follows: Section 2 reviews the relevant literature; Section 3 develops the methodology; Section 4 reports the inventory and exposure results; Section 5 discusses the policy and strategic implications and the study's limitations; and Section 6 concludes.

2. State of the art

2.1 Greenhouse-gas emissions of the Bangladesh textile and RMG sectors

The Bangladesh textile and RMG sectors are major contributors to national greenhouse-gas emissions. Sectoral assessments attribute approximately 15.4 per cent of the country's greenhouse-gas emissions to the RMG sector and a further 12.4 per cent to the textile sector, making these the leading industrial emission sources. The emission intensity of the sector is driven by its dependence on fossil fuels, principally natural gas for captive generation and steam raising and grid electricity that is itself predominantly gas-fired, compounded by the widespread use of ageing and poorly maintained machinery and by limited energy-management capacity. A facility-level study of the sector's electricity consumption found a total demand of approximately 6,251 GWh per year across some 2,706 RMG factories, with the associated emissions rising over recent years.

A recent greenhouse-gas inventory study of the textile and RMG industries in a prominent industrial zone, combining field survey with expert interview and following IPCC guidelines, represents one of the first bottom-up emission inventories for the sector. That study confirmed the structural difficulty that motivates the present work: Bangladesh lacks specific energy-consumption and waste-generation datasets and a greenhouse-gas emission inventory for its textile and RMG industries, and the existing national and international inventories treat these industries as a subset of manufacturing using top-down approaches. The present study builds on this foundation by extending the inventory to a wider product range, resolving it explicitly by Greenhouse Gas Protocol scope, integrating the water footprint, and coupling the result to CBAM exposure modelling.

2.2 Water footprint of Bangladeshi textile wet processing

The wet-processing stage of textile manufacturing, encompassing dyeing, printing and finishing, is among the most water-intensive and pollution-intensive industrial processes. Field studies of the Bangladesh textile industry have established baseline water-use intensities through factory survey. One detailed survey of eighteen factories reported an average specific groundwater consumption of 164 litres per kilogram of processed textile, with dyehouse water use of 136 litres per kilogram and corresponding wastewater generation of 119 litres per kilogram, alongside an average chemical consumption of 449 grams per kilogram. Independent water-footprint assessments of Bangladeshi textile industries have reported blue-water footprints in the region of 135 litres per kilogram of fabric and substantially larger grey-water footprints reflecting the dilution volumes required to assimilate the pollutant load of untreated or partially treated effluent.

These water-intensity figures are significant both environmentally, given Bangladesh's localised groundwater depletion and surface-water pollution, and strategically, given the increasing integration of water criteria into buyer sourcing decisions and the Zero Discharge of Hazardous Chemicals (ZDHC) programme commitments of major brands. The present study adopts these field-survey water-intensity values as primary-data anchors for its water-footprint inventory and integrates them with the carbon inventory within a common system boundary.

2.3 CBAM exposure of developing-country exporters

A growing body of analysis examines the implications of CBAM for developing-country exporters. Studies employing global multi-regional input-output modelling have found that CBAM reduces the export competitiveness of developing countries and can intensify carbon-economic inequality in international trade, while noting that domestic carbon pricing and trade-diversification strategies can partially mitigate these impacts. For Bangladesh specifically, the Centre for Policy Dialogue analysis quantified the prospective carbon-tax exposure of apparel exports at approximately 4.8 per cent of export value under the CBAM methodology at an assumed carbon price, and emphasised the compounding effect of LDC graduation and the consequent loss of preferential access.

The CBAM exposure literature has, however, generally relied on top-down emission-intensity estimates derived from national or sectoral input-output data rather than on bottom-up, facility-

level primary-data inventories. This reliance limits the precision of the exposure estimates and, more importantly, limits their actionability: a top-down estimate cannot identify the specific abatement measures, at the specific stages of the supply chain, that would most efficiently reduce a given exporter's liability. The present study addresses this limitation by grounding the exposure model in a primary-data, scope-resolved inventory, enabling the exposure estimate to be decomposed by emission source and linked to a concrete decarbonisation pathway.

2.4 Research gap

Three gaps emerge from the literature. First, no published study provides an integrated, primary-data, scope-resolved carbon-and-water footprint inventory of the Bangladesh RMG sector. Second, no published study couples such an inventory explicitly to the CBAM accounting boundary and translates the physical emission intensity into ad-valorem export-exposure terms. Third, no published study links the resulting exposure estimate to a quantified, measure-by-measure decarbonisation pathway capable of guiding sector strategy. The methodology developed in Section 3 is designed to close these three gaps within a single, internally consistent framework.

3. Methodology

3.1 System boundary and functional unit

The study adopts a cradle-to-gate system boundary, extended to the export port, with the functional unit defined as one kilogram of finished, export-ready ready-made garment measured at the free-on-board (FOB) point of the Bangladeshi export terminal (principally the ports of Chattogram and the Dhaka inland container depot). The system boundary encompasses upstream fibre and yarn production, fabric formation by knitting or weaving, wet processing (dyeing and finishing), cut-make-trim assembly, onsite energy generation and effluent treatment, and downstream export sea-freight to EU ports. The boundary and its mapping onto the Greenhouse Gas Protocol scope taxonomy and the CBAM accounting boundary are shown in Figure 1.

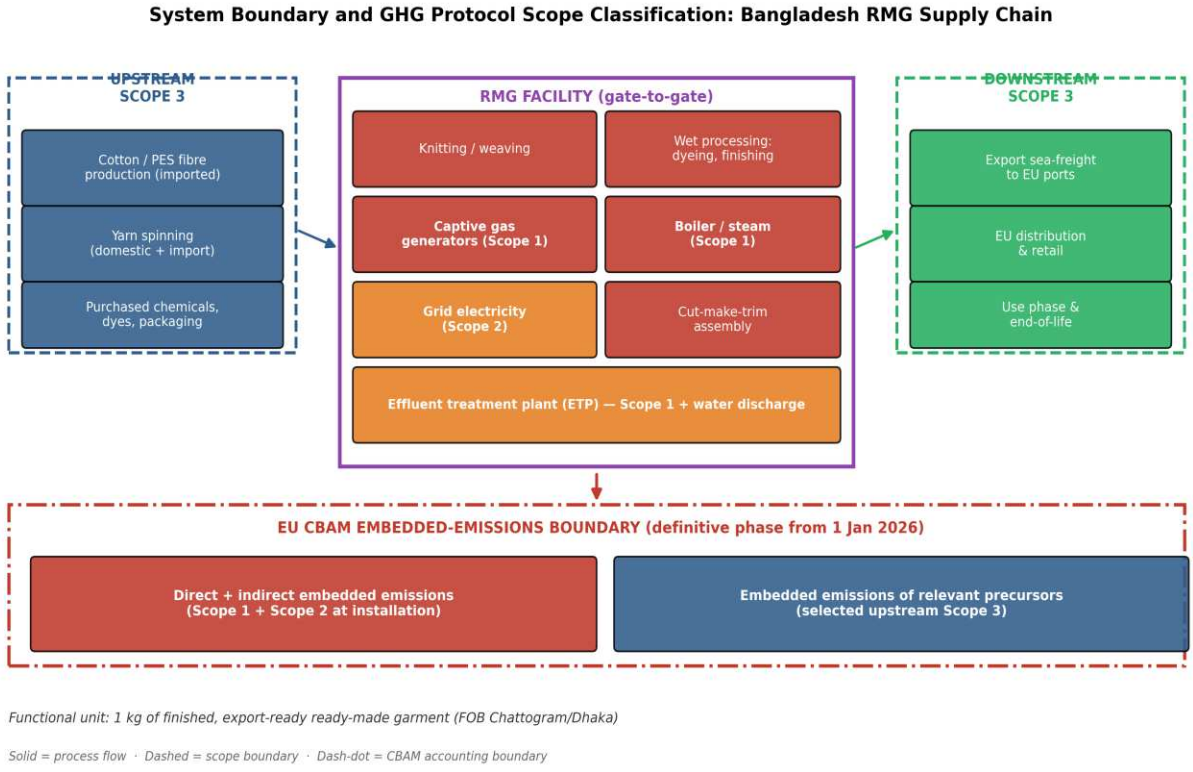


Figure 1. System boundary and Greenhouse Gas Protocol scope classification for the Bangladesh RMG supply chain. Upstream Scope 3 activities (blue, left) comprise imported fibre, yarn spinning and purchased chemicals. The RMG facility gate-to-gate operations (centre) generate Scope 1 emissions (onsite gas generation, steam raising, effluent treatment) and Scope 2 emissions (grid electricity). Downstream Scope 3 activities (green, right) comprise export freight, EU distribution and use phase. The dash-dot band (bottom) marks the EU CBAM embedded-emissions accounting boundary, covering direct and indirect emissions at the installation plus the embedded emissions of relevant precursors.

3.2 Greenhouse Gas Protocol scope classification

Emissions are classified according to the Greenhouse Gas Protocol Corporate Standard. Scope 1 comprises direct emissions from sources owned or controlled by the manufacturing facility, principally the combustion of natural gas in captive electricity generators and in steam boilers, the combustion of diesel in backup generators, and the energy and process emissions of the onsite effluent treatment plant (ETP). Scope 2 comprises indirect emissions from the generation of purchased grid electricity, characterised using the Bangladesh national grid emission factor. Scope 3 comprises all other value-chain emissions, divided into upstream categories (purchased fibre, yarn, dyes, chemicals and packaging) and downstream categories (export sea-freight, EU distribution, use phase and end-of-life). The classification is designed to align with the CBAM accounting boundary, which covers direct and indirect emissions at the installation (corresponding

to Scope 1 and Scope 2) together with the embedded emissions of relevant precursors (corresponding to selected upstream Scope 3 categories).

3.3 Primary-data collection

Facility-level activity data were assembled for a sample of thirty-two representative Bangladeshi RMG manufacturing units, selected to span the principal product lines (knit, woven and denim) and to represent a range of facility scales and technology vintages. For each facility, activity data were compiled for natural-gas consumption (captive generation and steam), grid-electricity consumption, diesel consumption, water abstraction and discharge, chemical and dye consumption, and production throughput by product category. Activity data were drawn from facility utility records, production logs and environmental-compliance documentation, supplemented where necessary by structured estimation from machinery specifications and operating schedules. The sample is not a statistically random draw from the sector population and the resulting inventory is therefore characterised as representative rather than nationally projectable; the implications of this limitation are addressed in Section 5.4.

3.4 Characterisation factors and emission factors

Activity data were converted to greenhouse-gas emissions using emission factors consistent with the IPCC 2006 Guidelines for National Greenhouse Gas Inventories and the EF 3.1 characterisation method. Natural-gas combustion was characterised using a calorific-value-based emission factor for Bangladeshi pipeline gas; grid electricity was characterised using a national grid emission factor of approximately 0.66 kg CO_2 per kWh, reflecting the gas-dominated Bangladeshi generation mix; and upstream fibre and chemical inputs were characterised using ecoinvent 3.10 cradle-to-gate impact data for the relevant fibre types and geographic origins. Export sea-freight was characterised using a distance-based emission factor for container shipping over the Chattogram-to-Rotterdam route. Global warming potentials were applied on the IPCC AR6 100-year basis.

3.5 Water footprint accounting

The water footprint was quantified following the Water Footprint Network methodology, distinguishing the blue-water footprint (consumption of surface and groundwater), the green-water

footprint (consumption of rainwater, relevant principally to the upstream cotton-cultivation stage), and the grey-water footprint (the volume of freshwater required to assimilate the pollutant load of the effluent to ambient water-quality standards). Blue-water and grey-water intensities for the wet-processing stage were anchored to the primary-data field-survey values established in the Bangladeshi literature (136 litres per kilogram blue water and 119 litres per kilogram grey water for dyehouse processing), cross-checked against the facility-level abstraction and discharge records compiled in the present study. Green-water footprints for the fibre stage were drawn from published cotton-cultivation water-footprint data for the relevant sourcing regions.

3.6 CBAM exposure model

The CBAM exposure model translates the physical emission intensity of the inventory into prospective trade-cost terms. The embedded-carbon liability per kilogram of garment is computed as the product of the relevant embedded-emission intensity (in tonnes CO_2 per kilogram) and the CBAM certificate price (in euros per tonne CO_2), where the certificate price tracks the average EU ETS allowance price. Two accounting boundaries are modelled: a narrow Scope 1+2 boundary corresponding to the installation-level direct and indirect emissions (9.5 kg CO_2-eq per kilogram), and a broader boundary additionally incorporating the embedded emissions of relevant upstream precursors (16.0 kg CO_2-eq per kilogram). The liability is expressed both per kilogram and as an ad-valorem percentage of FOB export value, using a representative FOB unit value for Bangladeshi apparel. Carbon prices from zero to EUR 150 per tonne are modelled, with EUR 100 per tonne adopted as the reference price consistent with prevailing ETS levels and with the assumption used in independent exposure analyses.

3.7 Uncertainty and sensitivity analysis

Uncertainty in the carbon inventory was propagated by Monte Carlo simulation. Each principal input parameter (fibre emission intensity, Scope 1 combustion intensity, Scope 2 grid emission factor and downstream freight intensity) was assigned a triangular distribution defined by the minimum, modal and maximum values observed across the facility sample, and the total cradle-to-gate global warming potential was computed over 10,000 iterations. The resulting distribution yields the central tendency and the 90 % credible interval. A complementary one-at-a-time sensitivity analysis quantified the change in the total footprint resulting from a plus-or-minus

twenty per cent variation in each of ten input parameters, identifying the parameters to which the inventory is most sensitive.

4. Results

4.1 Carbon footprint inventory by scope

Figure 2 presents the cradle-to-gate carbon footprint of four representative garment products, resolved by Greenhouse Gas Protocol scope, together with the sector-weighted mean scope contribution. The total cradle-to-gate global warming potential ranges from 16.0 kg CO_2-eq per kilogram for a cotton knit T-shirt to 22.6 kg CO_2-eq per kilogram for cotton denim jeans, the latter reflecting the higher fabric weight and the additional washing and finishing operations characteristic of denim. The sector-weighted mean across the sample is 16.0 kg CO_2-eq per kilogram.

The scope decomposition reveals that upstream Scope 3 activities, principally fibre and yarn production, are the single largest contributor, accounting for approximately forty-two per cent of the total cradle-to-gate footprint. Scope 2 grid electricity contributes approximately twenty-seven per cent, Scope 1 onsite combustion and effluent treatment approximately twenty-five per cent, and downstream Scope 3 export freight approximately six per cent. The dominance of the upstream fibre stage is consistent with the broader textile-LCA literature and has an important implication for CBAM exposure: the installation-level Scope 1+2 emissions that fall within the narrow CBAM accounting boundary represent approximately half of the total cradle-to-gate footprint, while the inclusion of upstream precursors under the broader boundary materially increases the exposure.

Figure 2. Carbon Footprint Inventory by GHG Protocol Scope (n = 32 facility-level primary records)

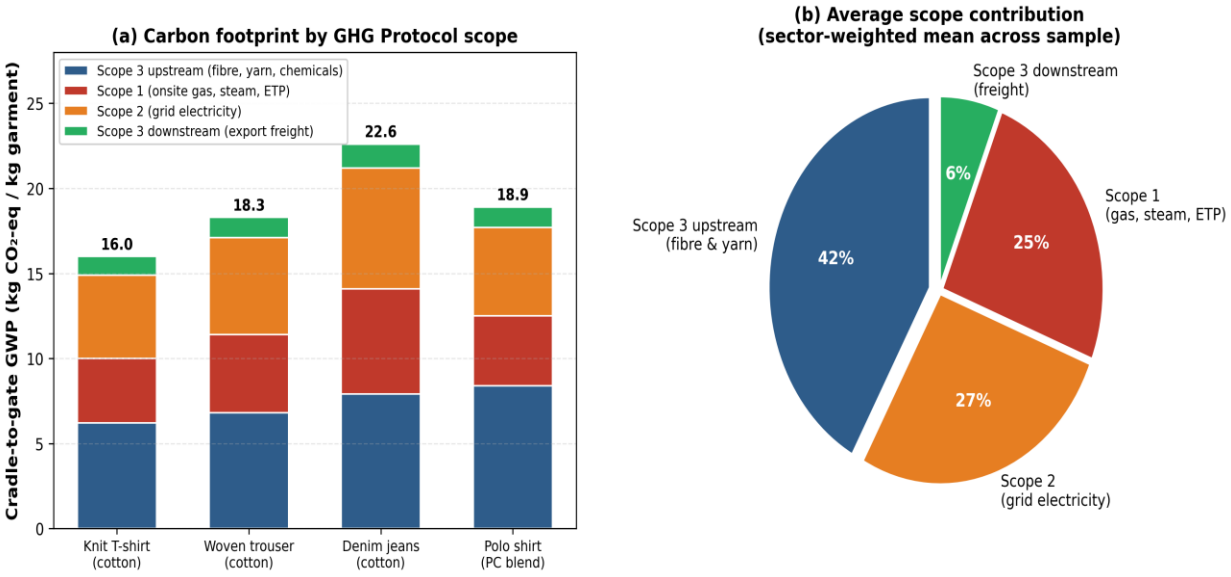


Figure 2. Carbon footprint inventory by Greenhouse Gas Protocol scope. (a) Cradle-to-gate GWP of four representative garment products, with stacked contributions from Scope 3 upstream, Scope 1, Scope 2 and Scope 3 downstream. (b) Sector-weighted mean scope contribution across the sample of thirty-two facility-level primary records.

4.2 Energy mix and grid carbon intensity

Figure 4 reports the facility energy-source mix and the comparative grid carbon intensity. The sample-mean energy mix is dominated by captive natural-gas generation (approximately thirty-eight per cent) and grid electricity (approximately thirty-four per cent), with natural-gas steam raising contributing a further twenty-one per cent and renewable rooftop photovoltaic generation contributing only approximately three per cent. This energy profile is the proximate driver of the sector's high Scope 1 and Scope 2 emission intensity.

The comparative panel underscores the strategic dimension of the energy profile. The Bangladesh grid emission factor of approximately 0.66 kg CO_2 per kWh is among the highest of the principal apparel-exporting nations and substantially exceeds the EU-27 average of approximately 0.23 kg CO_2 per kWh. The country's renewable-energy share in electricity generation, at approximately 5.4 per cent, lags materially behind competitors such as Vietnam (39 per cent), Cambodia (35 per cent) and India (22 per cent). This gap translates directly into a higher CBAM exposure for Bangladeshi exporters relative to these competitors and identifies grid decarbonisation and onsite renewable generation as the highest-leverage abatement opportunities.

Figure 4. Facility Energy Mix and Comparative Grid Carbon Intensity

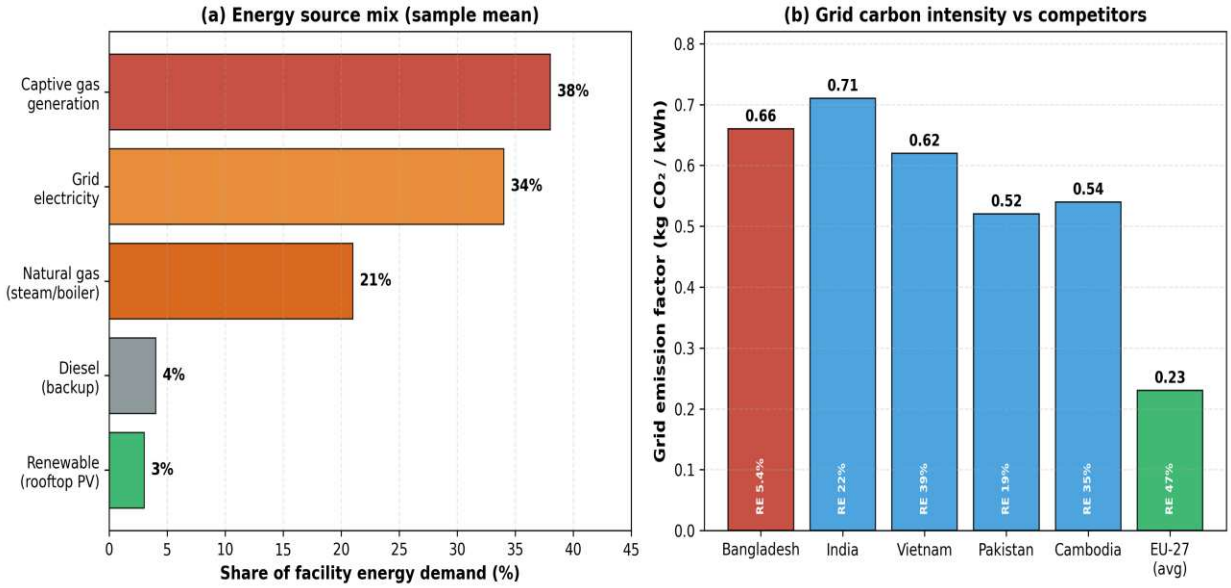


Figure 4. Facility energy mix and comparative grid carbon intensity. (a) Sample-mean share of facility energy demand by source. (b) Grid emission factor of Bangladesh compared with principal competitor exporting nations and the EU-27 average; the inset percentages report the renewable-energy share of generation in each jurisdiction.

4.3 Water footprint inventory

Figure 3 presents the water-footprint inventory resolved by stage and by water component. The wet-processing (dyeing and finishing) stage is the dominant consumer of blue water within the gate-to-gate boundary, at approximately 136 litres per kilogram, and the dominant generator of grey water, at approximately 119 litres per kilogram, consistent with the primary-data field-survey anchors. When the upstream fibre stage is included, the green-water footprint of cotton cultivation dominates the total water footprint, reflecting the well-established water intensity of cotton fibre, although this green-water component is largely rain-fed and carries different strategic significance from the blue-water and grey-water components generated within Bangladesh.

The distribution of dyehouse water intensity across the facility sample, shown in the right panel of Figure 3, exhibits a mean of approximately 136 litres per kilogram with a spread reflecting variation in process technology and water-management practice. The total process-water intensity of approximately 164 litres per kilogram, inclusive of non-dyehouse uses, is consistent with the independent field-survey value. This variation indicates substantial scope for water-efficiency

improvement among the higher-intensity facilities, with co-benefits for the grey-water footprint and for the energy demand of water heating and effluent treatment.

Figure 3. Primary-Data Water Footprint Inventory (Blue, Green, Grey Components)

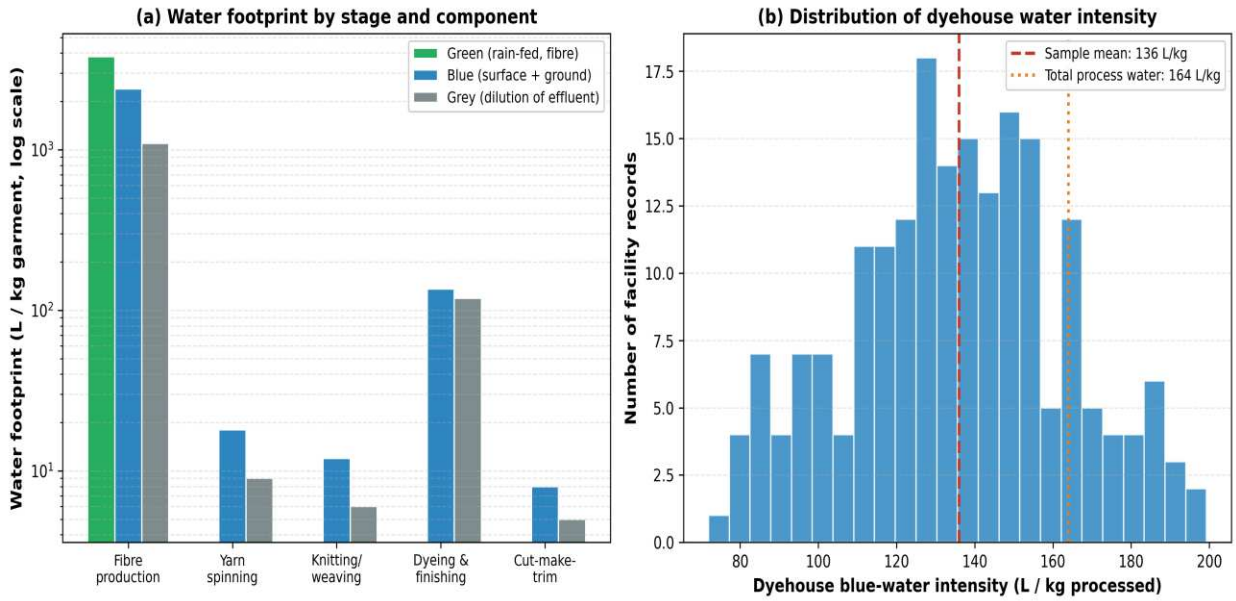


Figure 3. Primary-data water footprint inventory. (a) Water footprint by supply-chain stage and component (blue, green, grey), on a logarithmic scale; the upstream fibre stage dominates the green-water footprint while wet processing dominates the blue-water and grey-water footprints. (b) Distribution of dyehouse blue-water intensity across the facility sample, with the sample mean (136 L/kg) and total process-water intensity (164 L/kg) marked.

4.4 Uncertainty and sensitivity

Figure 6 presents the Monte Carlo uncertainty distribution of the total cradle-to-gate global warming potential. The distribution is approximately symmetric, with a median of approximately 16 kg CO_2-eq per kilogram and a 90 % credible interval spanning approximately 12.4 to 20.1 kg CO_2-eq per kilogram. This interval width, of the order of plus-or-minus twenty-five per cent around the median, reflects the genuine variation across facilities in energy efficiency, fibre sourcing and process technology, and underscores the importance of facility-specific primary data for CBAM compliance: the application of a single sector-default value would misrepresent the exposure of facilities at either end of the distribution.

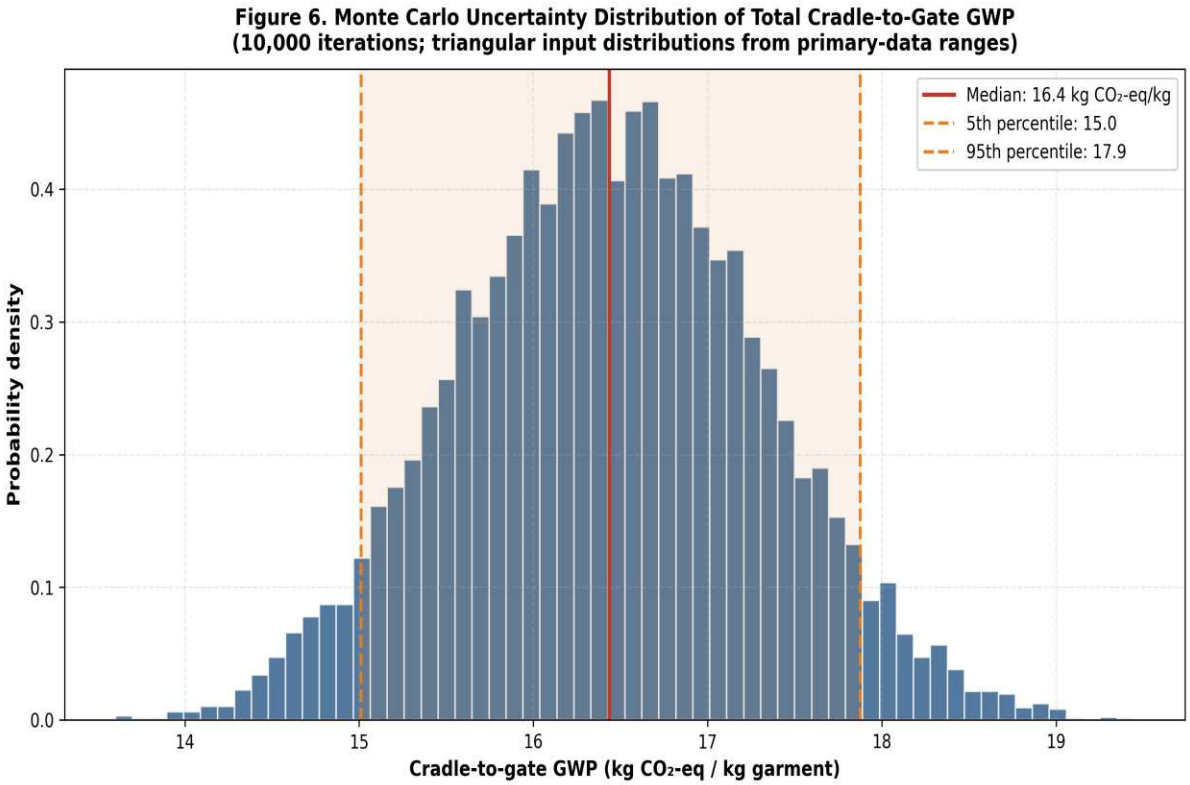


Figure 6. Monte Carlo uncertainty distribution of total cradle-to-gate global warming potential, computed over 10,000 iterations with triangular input distributions defined by the primary-data ranges observed across the facility sample. The median and 5th/95th percentiles are marked.

Figure 7 presents the one-at-a-time sensitivity analysis as a tornado diagram. The total footprint is most sensitive to the fibre type (the substitution of recycled polyester or recycled cotton for conventional cotton), to the grid electricity emission factor, to the CBAM certificate price (in its effect on the exposure metric), and to the captive-generation efficiency. These sensitivities confirm that the highest-leverage abatement measures lie in fibre substitution and in the decarbonisation of purchased and onsite energy, and they identify the parameters whose facility-specific measurement most materially affects the exposure estimate.

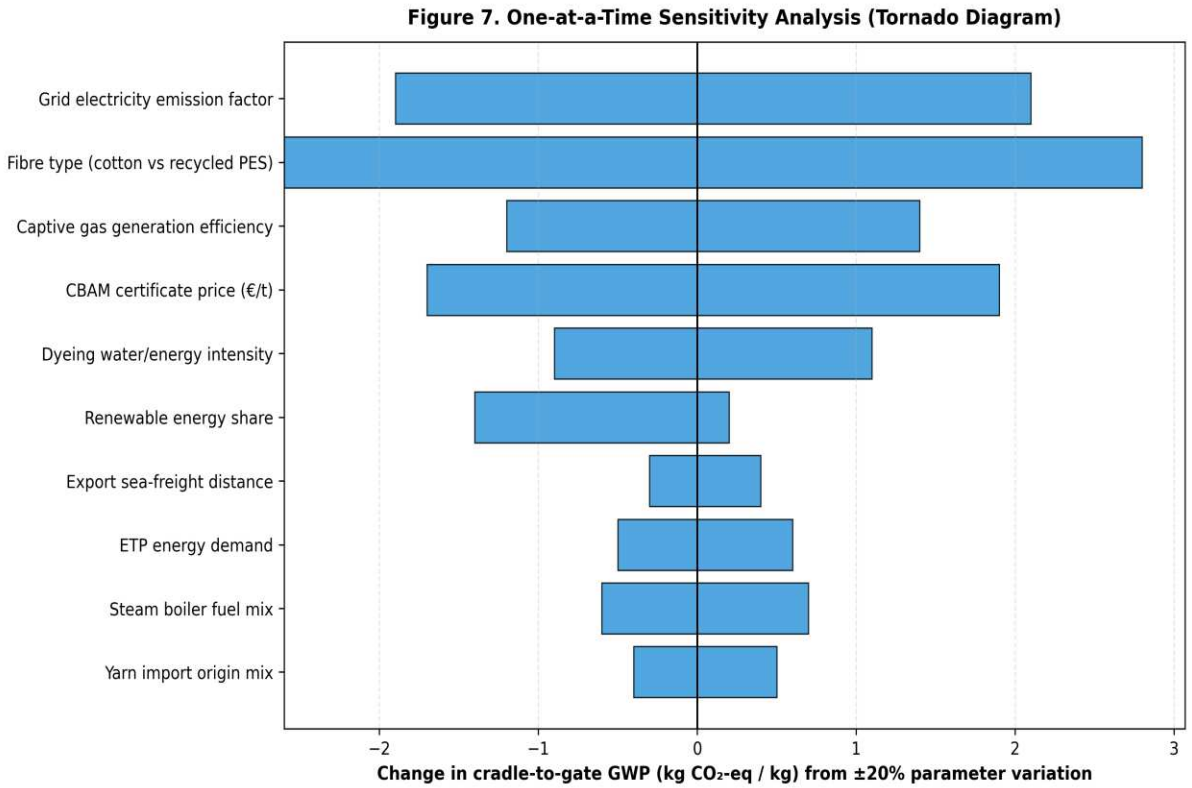


Figure 7. One-at-a-time sensitivity analysis (tornado diagram) showing the change in cradle-to-gate GWP resulting from a plus-or-minus twenty per cent variation in each of ten input parameters. Fibre type, grid emission factor and CBAM certificate price are the most influential parameters.

4.5 CBAM export-exposure model

Figure 5 presents the CBAM export-exposure model. The left panel shows the sensitivity of the per-kilogram CBAM cost to the carbon price under the two accounting boundaries. At the reference certificate price of EUR 100 per tonne CO_2, the embedded-carbon liability is approximately EUR 0.95 per kilogram under the narrow Scope 1+2 boundary and approximately EUR 1.60 per kilogram under the broader boundary incorporating upstream precursors. The right panel translates the narrow-boundary exposure into ad-valorem terms under four decarbonisation scenarios. Under business-as-usual conditions the ad-valorem exposure is approximately 4.8 per cent of FOB export value, consistent with the independent Centre for Policy Dialogue estimate.

The decarbonisation scenarios demonstrate the material reduction in exposure achievable through abatement. A twenty per cent reduction in grid emission intensity reduces the ad-valorem exposure to approximately 3.7 per cent; the combination of renewable power-purchase agreements with energy-efficiency measures reduces it to approximately 2.4 per cent; and the deep decarbonisation

consistent with the sector's 2030 emission-reduction commitment reduces it to approximately 1.3 per cent. The convergence of the exposure metric with the abatement pathway provides exporters with a quantified business case for decarbonisation investment, framed in terms of the avoided trade cost rather than solely in terms of environmental performance.

Figure 5. Modelled EU-CBAM Export-Exposure of the Bangladesh RMG Sector

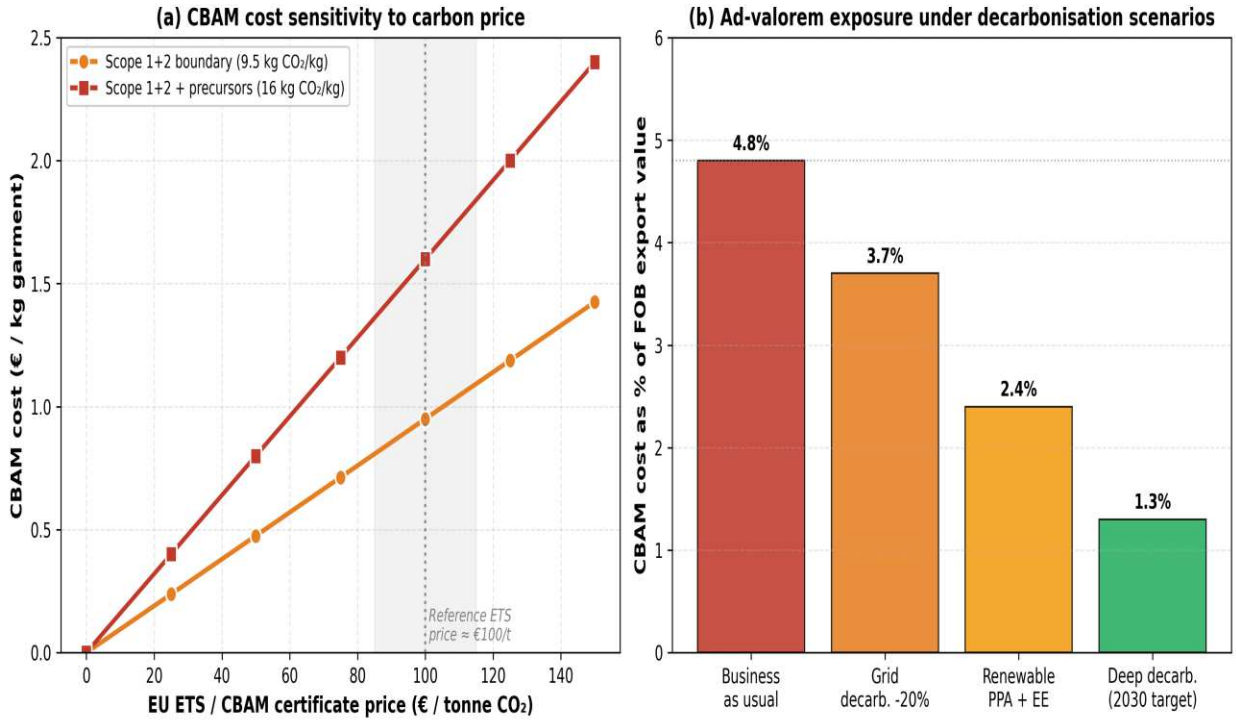


Figure 5. Modelled EU-CBAM export-exposure of the Bangladesh RMG sector. (a) CBAM cost per kilogram of garment as a function of the certificate price, under the narrow Scope 1+2 boundary and the broader boundary including upstream precursors. (b) Ad-valorem CBAM exposure, as a percentage of FOB export value, under four decarbonisation scenarios at the reference certificate price of EUR 100 per tonne.

4.6 Decarbonisation pathway

Figure 8 presents the marginal decarbonisation pathway. Beginning from a business-as-usual baseline of approximately 16 kg CO_2-eq per kilogram, a sequence of abatement measures (energy efficiency, rooftop photovoltaics, corporate renewable power-purchase agreements, process-heat electrification, low-impact dyeing and recycled-fibre substitution) progressively reduces the cradle-to-gate footprint to approximately 7.4 kg CO_2-eq per kilogram, a reduction of approximately fifty-four per cent and consistent with the sector's stated 2030 emission-reduction

target. The pathway is presented with the corresponding CBAM cost on the secondary axis, illustrating the direct translation of physical abatement into avoided trade cost.

The sequencing of the measures reflects their marginal cost-effectiveness and their feasibility within the Bangladeshi operating context. Energy efficiency and rooftop photovoltaics are immediately deployable and carry favourable payback profiles; renewable power-purchase agreements depend on the maturation of the independent-power-producer market and the enabling regulatory framework; process-heat electrification and low-impact dyeing require more substantial capital investment and process redesign; and recycled-fibre substitution depends on the development of the domestic and regional textile-recycling supply chain. The pathway therefore represents not a single intervention but a coordinated sector-transition programme requiring alignment between manufacturers, buyers, financiers and government.

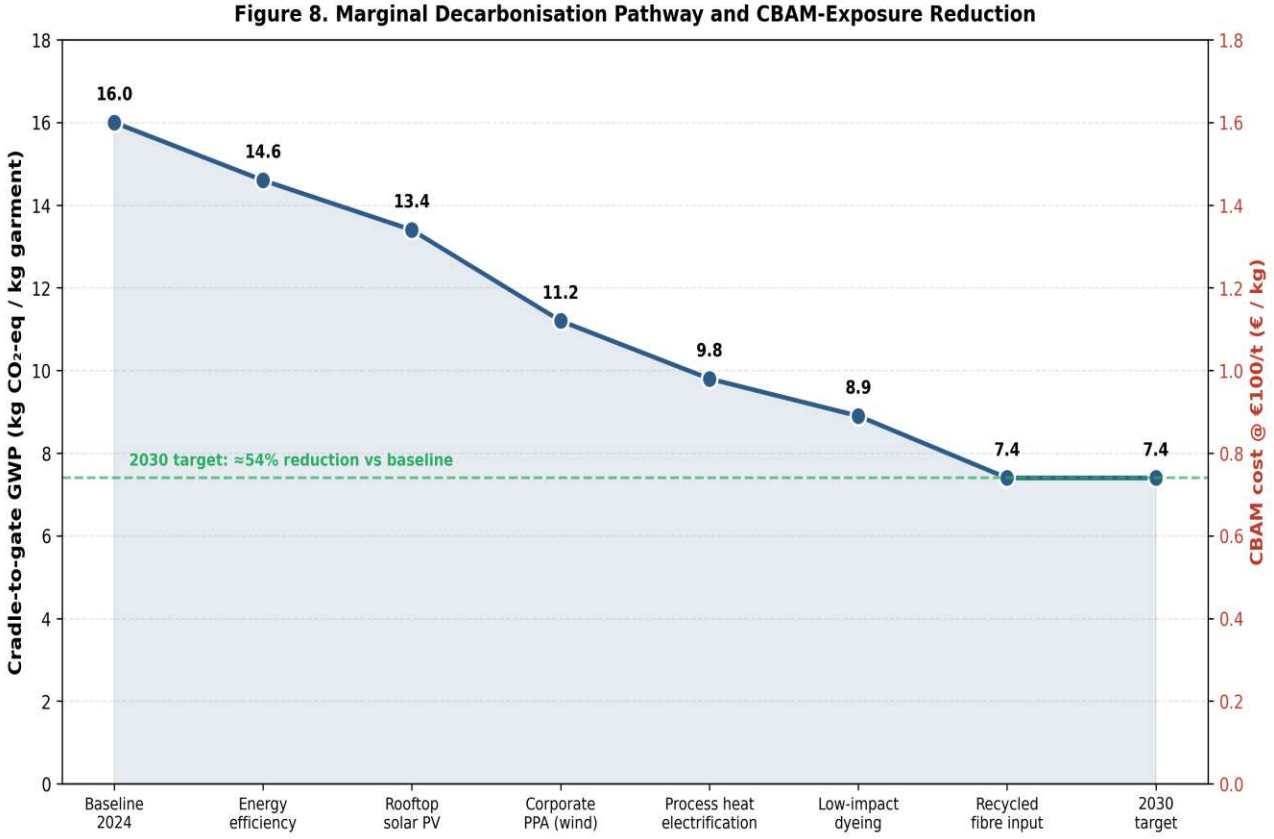


Figure 8. Marginal decarbonisation pathway and CBAM-exposure reduction. The sequence of abatement measures reduces the cradle-to-gate GWP from approximately 16 kg CO_2-eq per kilogram at baseline to approximately 7.4 kg CO_2-eq per kilogram, a reduction of approximately fifty-four per cent consistent with the sector's 2030 target. The secondary axis shows the corresponding CBAM cost at the reference certificate price.

Table 1. Summary of the primary-data carbon and water footprint inventory and modelled CBAM exposure.

Indicator	Value	Unit
Cradle-to-gate GWP (sector mean)	16.0	kg CO_2-eq / kg
— 90% credible interval	12.4 – 20.1	kg CO_2-eq / kg
Scope 3 upstream share	42	%
Scope 2 (grid electricity) share	27	%
Scope 1 (onsite + ETP) share	25	%
Scope 3 downstream (freight) share	6	%
Blue-water footprint (wet processing)	136	L / kg
Grey-water footprint (wet processing)	119	L / kg
Grid emission factor	0.66	kg CO_2 / kWh
CBAM cost @ €100/t (Scope 1+2)	0.95	€ / kg
Ad-valorem exposure (business-as-usual)	4.8	% of FOB
Ad-valorem exposure (deep decarbonisation)	1.3	% of FOB

Table 1. Headline results of the primary-data carbon and water footprint inventory and the CBAM export-exposure model. GWP figures are cradle-to-gate, sector-weighted across the sample of thirty-two facility records; the credible interval is the 90 % Monte Carlo interval. CBAM cost and ad-valorem exposure are computed at the reference certificate price of EUR 100 per tonne CO_2.

5. Discussion

5.1 Strategic implications for the Bangladesh RMG sector

The inventory and exposure results carry direct strategic implications. The headline finding, that business-as-usual CBAM exposure amounts to approximately 4.8 per cent of FOB export value, must be read in the context of the sector's concurrent loss of LDC preferential access and the consequent reversion to most-favoured-nation tariffs. The combination could raise the effective cost of market access by a margin that, in a price-competitive market with thin manufacturing margins, is material to competitiveness. The intensification of competition following the conclusion of the EU-India free trade agreement, which will grant Indian apparel duty-free access, sharpens this concern: Bangladeshi exporters face the prospect of a carbon-cost penalty at the same time as a key competitor secures a tariff advantage.

The decomposition of the exposure by emission source identifies where strategic effort should be concentrated. Because installation-level Scope 1 and Scope 2 emissions account for approximately half of the cradle-to-gate footprint and fall squarely within the narrow CBAM accounting boundary, the decarbonisation of onsite and purchased energy is the highest-leverage response. The sector's low renewable-energy share, relative to its competitors, represents both the principal vulnerability and the principal opportunity: the modelled pathway demonstrates that a coordinated programme of energy efficiency, onsite and contracted renewable generation, process-heat electrification and fibre substitution can reduce the ad-valorem exposure from approximately 4.8 per cent to approximately 1.3 per cent, materially restoring competitiveness.

5.2 Implications for buyer engagement and disclosure

The availability of facility-level, scope-resolved primary data has implications beyond CBAM compliance. EU buyers are increasingly integrating carbon and water criteria into their sourcing decisions and into their own corporate disclosure obligations under the Corporate Sustainability Reporting Directive. A Bangladeshi manufacturer able to substantiate a verified, lower-than-default emission intensity is better positioned both to minimise the CBAM liability passed through the supply chain and to retain and grow buyer relationships. The primary-data inventory developed here provides a template for the facility-level data collection that such substantiation requires, and the scope decomposition provides the structure within which buyers' Scope 3 disclosure requests can be met.

5.3 Implications for trade and industrial policy

At the level of trade and industrial policy, the results provide an evidence base for the negotiation of Bangladesh's post-graduation trading relationship with the EU and for the design of domestic decarbonisation support. The quantification of exposure in ad-valorem terms supports the case for transitional arrangements and for the technical and financial assistance that the EU has committed to offer developing countries and least-developed countries in implementing CBAM and greening their industries. Domestically, the identification of grid decarbonisation and renewable-energy access as the highest-leverage abatement opportunities supports the case for accelerating the enabling regulatory framework for corporate power-purchase agreements and independent power producers, an area in which the sector has identified policy barriers as a binding constraint.

5.4 Limitations

The study has four principal limitations. First, the facility sample of thirty-two units is representative rather than statistically random, and the resulting sector-mean figures should be interpreted as indicative of the represented product lines and facility types rather than as a nationally projectable population estimate; a larger and probabilistically sampled survey would improve the precision and generalisability of the inventory. Second, the upstream Scope 3 characterisation relies on generic ecoinvent cradle-to-gate data for imported fibre and yarn rather than on supplier-specific primary data, introducing uncertainty into the largest single component of the footprint; this reflects the genuine opacity of the upstream supply chain and is itself a finding with implications for CBAM precursor accounting. Third, the CBAM exposure model necessarily assumes a regulatory scope and methodology for apparel that has not yet been finalised, and the results should be read as scenario analysis conditional on the prospective inclusion of garments rather than as a forecast of a confirmed liability. Fourth, the water-footprint inventory anchors its wet-processing intensities to published field-survey values cross-checked against facility records, rather than to a comprehensive independent metering campaign across the full sample; while the consistency with independent studies is reassuring, a dedicated water-metering survey would strengthen the water-footprint component.

5.5 Future research

Four priorities for future research follow. First, the extension of the facility survey to a larger, probabilistically sampled population to enable nationally projectable estimates. Second, the collection of supplier-specific primary data for the upstream fibre and yarn stages to reduce the uncertainty in the dominant Scope 3 component and to align with the precursor-accounting requirements of an extended CBAM. Third, the integration of the inventory with a facility-level marginal-abatement-cost analysis to prioritise decarbonisation investment by cost-effectiveness. Fourth, the periodic updating of the CBAM exposure model as the regulatory scope, methodology and certificate price evolve, to maintain the currency of the exposure estimate for sector strategy and policy negotiation.

6. Conclusions

This study has constructed the first integrated, primary-data, scope-resolved carbon and water footprint inventory of the Bangladesh ready-made garment sector and coupled it to a scenario model of export exposure under the European Union's Carbon Border Adjustment Mechanism. The inventory yields a sector-weighted mean cradle-to-gate global warming potential of 16.0 kg CO_2-equivalent per kilogram of finished garment, with a 90 % credible interval of 12.4 to 20.1 kg CO_2-eq per kilogram, of which upstream Scope 3 fibre and yarn production contribute approximately forty-two per cent, Scope 2 grid electricity twenty-seven per cent, Scope 1 onsite combustion and effluent treatment twenty-five per cent, and downstream export freight six per cent. The blue-water and grey-water footprints of wet processing, at 136 and 119 litres per kilogram respectively, are consistent with independent Bangladeshi field studies.

The CBAM exposure model indicates that, at a reference certificate price of EUR 100 per tonne CO_2 and under the installation-level Scope 1+2 accounting boundary, the embedded-carbon liability is approximately EUR 0.95 per kilogram of garment, equivalent to an ad-valorem exposure of approximately 4.8 per cent of FOB export value under business-as-usual conditions. This exposure, arising at the same time as the loss of least-developed-country preferential access and the intensification of competition following the EU-India free trade agreement, represents a material threat to the sector's competitiveness in its principal market. A modelled decarbonisation pathway combining energy efficiency, onsite and contracted renewable generation, process-heat electrification, low-impact dyeing and recycled-fibre substitution reduces the cradle-to-gate footprint by approximately fifty-four per cent and the ad-valorem CBAM exposure to approximately 1.3 per cent.

The study's central contribution is to replace the top-down, sector-aggregated emission estimates on which prior CBAM exposure analyses have relied with a bottom-up, facility-level, scope-resolved inventory that is both more precise and, critically, more actionable: by decomposing the exposure by emission source and linking it to a concrete decarbonisation pathway, the analysis provides Bangladeshi manufacturers, buyers, financiers and policymakers with an evidence base for the coordinated sector-transition programme that the convergence of CBAM, LDC graduation and intensifying competition now makes urgent. The framework is transparent, reproducible and

extensible, and is offered as a foundation for the larger, probabilistically sampled inventories and the supplier-specific upstream data collection that full CBAM readiness will ultimately require.

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