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Future disposal surge

A new quantification approach for predicting waste from external thermal insulation composite systems in Germany

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Abstract

This study quantifies external thermal insulation composite systems (ETICS), in particular expanded polystyrene (EPS) as the insulation layer, installed in Germany between 1969 and 2022. Employing a bottom-up approach, it conducts mass quantification, localization at the NUTS-3 level, determination of installation years, and prediction of future waste for both ETICS in general and EPS ETICS specifically. The methodology involves categorizing the German residential and non-residential building stock into further subcategories and construction age classes to determine their respective insulation parameters such as insulation rate and thickness providing insights into the distribution of ETICS quantities across building categories and types, construction years, and administrative districts. Additionally, waste stream predictions are carried out through surveys on ETICS lifetimes and single-house-level sampling of probabilistic lifetimes. The findings project a quadrupling of annual EPS waste generation from ETICS by 2050 compared to today, with 79% attributed to residential and 21% to non-residential buildings, predominantly in urban areas. The results of the ETICS waste prediction indicate that currently established disposal routes are unfit to handle future waste generation, underlining the importance of alternative recycling paths for ETICS and improved waste disposal policies.

KEYWORDS

external thermal insulation composite systems (ETICS), expanded polystyrene (EPS), mass quantification and localization, waste generation prediction, circular economy, building stock

1 | INTRODUCTION

In 1957, the inaugural installation of an external thermal insulation composite system (ETICS) took place on a residential building in Berlin, Germany. Suisse and Austria applied exterior facade insulation shortly thereafter. However, it was not until the fuel crisis of the early 1970s and the resulting rise in energy prices that the idea of external thermal building insulation gained traction (Michalak, 2021). To increase energy efficiency in the building sector, numerous countries have since passed thermal insulation regulations for both residential (*RBs*) and non-residential buildings (*NRBs*). The first such regulation, the German “Wärmeschutzverordnung”, was introduced in 1977.

ETICS comprise different layers fitted on the exterior wall, including an adhesive, insulation material, such as expanded polystyrene (EPS) or mineral wool, dowels, a reinforcing mesh typically made of fiberglass and a base, and protective coating like textured acrylic.

According to the German Association for Insulation Systems Render and Mortar (VDPM), around 1.35 billion m^2 of ETICS have been installed in Germany between 1960 and 2022, with EPS as the insulation material for 80% of the German building stock. Mineral wool and wood fiber insulation play minor roles (Schwitalla et al., 2023). During its use, EPS demonstrates numerous benefits, including excellent thermal insulation, lightweight properties, cost-effectiveness, and resistance to moisture and pests (Yucel et al., 2003). In addition, EPS has a relatively low environmental impact compared to other wall insulation materials (Densley Tingley et al., 2015). Nevertheless, effectively managing the end-of-life (EoL) treatment of EPS insulation presents ongoing challenges, that is, contamination with toxic flame retardant hexabromocyclododecane (HBCD) and current deconstruction practices leading to unsorted construction waste (Heller & Flamme, 2020). With widespread installation starting in the 1970s and an estimated lifespan of 40–60 years (Albrecht & Schwitalla, 2015) for ETICS, the necessity for extensive EoL treatment of EPS waste from ETICS has been limited so far. Currently, municipal solid waste incineration (MSWI) plants serve as the predominant treatment method for EPS waste from ETICS. This approach is highly linear in its use of fossil resources, contrasting the European strategic orientation toward a circular economy (European Commission, 2015). Economically, MSWI plants operate at near-maximum capacity (Heller & Flamme, 2020), and the high calorific value of EPS poses technical hurdles even with current low waste volumes (Mark et al., 2015), leading to inflated expenses for EPS waste management (Lützau et al., 2024). Anticipated future trends suggest that these challenges will exacerbate, with the volume of EPS waste from ETICS projected to approximately double by 2030 and triple by 2050 compared to 2020 levels (Albrecht & Schwitalla, 2015; Heller, 2022). According to Schleier et al. (2022), this volume could even increase 10-fold between 2020 and 2040. Novel recycling methods for EPS waste from ETICS beyond incineration and energy recovery have been developed and investigated. These include chemical recycling, for example, via pyrolysis, and physicochemical EPS recycling using "PolyStyreneLoop," which dissolves EPS in a specialized solvent. Moreover, mechanical recycling and material and energy utilization in cement plants are possible (Heller & Flamme, 2020). Establishing these recycling methods requires reliable data regarding occurring EPS waste masses from ETICS, along with their precise localization and temporal occurrence as prerequisites for designing and optimizing recovery and recycling networks and conducting techno-economic analyses.

The available data on ETICS waste generation are limited, with a particular lack of empirical data. This is partly because waste statistics often combine ETICS waste with construction and insulation waste, rather than listing them separately. Consequently, the volume of ETICS waste can only be estimated resulting in significant variability (Heller & Flamme, 2020). Existing estimations are usually "top-down" relying on aggregated production statistics for plastics, which are broken down by application into construction, EPS/XPS (extruded polystyrene), and finally EPS for ETICS applications (Albrecht & Schwitalla, 2015) or based on EPS production statistics (Lindner et al., 2020). Furthermore, some "top-down" approaches use installation statistics of ETICS, with separate indications of individual insulation materials, that is Schleier et al. (2022) and Schwitalla et al. (2023). The underlying data are provided by the German Association for Insulation Systems Render and Mortar (VDPM). However, calculating insulation material volumes and masses from installed ETICS coverage areas relies on assumptions regarding insulation thickness and insulation material density. Additionally, the data originate from the industry's professional association itself rather than scientific entities and therefore may be subject to potential conflicts of interest. Accordingly, there is a research gap concerning "bottom-up" waste generation analyses, as well as their local and temporal occurrence, that does not rely on industry-specific production statistics, static application splits, or sparse data from waste statistics. This paper addresses this research gap by presenting new methods (Section 2) and results (Section 3) for EPS-based ETICS quantification followed by a discussion (Section 4).

2 | METHODS

The developed approach constitutes a bottom-up methodology for estimating the volume of ETICS, particularly EPS-based, in a case study for Germany. It provides a breakdown of the anticipated annual post-demolition EPS waste from ETICS and their spatial distribution across all 401 German administrative districts (*ads*). This study focuses solely on post-use/ post-demolition EPS waste from ETICS, excluding other applications or production waste. The approach is structured into three parts: data collection and pre-processing (Section 2.1), data processing and calculations (Section 2.2), and sampling and forecasting (Section 2.3). Figure 1 provides a graphical overview of the methodology.

2.1 | Data collection and pre-processing

2.1.1 | Database combination: Building stock data

In the first step, data on the German building stock are collected. For *RBs*, the main source of data is the German Census of 2011 and its continuation until 2022, provided by the German Federal Statistical Office. *RBs* are classified according to the German *RB* typology, in accordance with the TABULA (typology approach for building stock energy assessment) project (Loga et al., 2015). This typology classifies *RBs* into four base types: "single

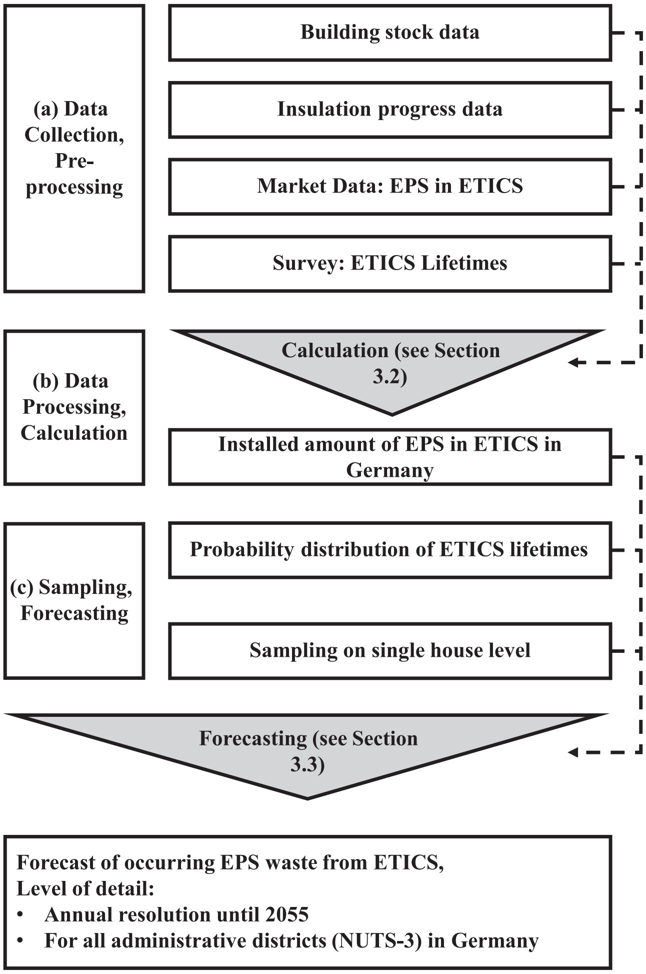


FIGURE 1 Illustration of the methodological approach. EPS, expanded polystyrene; ETICS, external thermal insulation composite system.

family house" (*SFH*), "terraced house" (*TH*), "multi-family house" (*MFH*), and "large multi-family house" (*LMH*). Regarding the year of construction, the typology differentiates between 12 construction age classes (*cacs*), listed in the supporting information (S-1).

For each building archetype, the typology lists typical values for external wall surface area, excluding windows and doors. Building data from the German Census can be mapped to this classification using the construction period, number of housing units per building, and whether the houses are detached or terraced.

In addition to the *RB* stock, *NRBs* are considered in the presented approach that are subject to the Building Energy Act (GEG) and therefore are obligated to undergo thermal insulation. For this, the *NRB* stock is divided into two main categories: service buildings (*SB*) and production buildings (*PB*) comprising a combined total of 17 subtypes, listed in the supporting information (S-1).

For the two main types of *NRBs*, the same *cacs* as for *RBs* are applied. Data regarding external wall areas for the two main *NRB* types and different *cacs* were taken from the German *NRB* typology (Hörner & Bischof, 2022), while information about the age distribution of the German *NRB* stock was derived from Hörner (2021). To achieve spatial distribution of *NRBs* on the NUTS-3 level of detail, construction completion statistics from the German Federal Statistical Office have been utilized to allocate the *NRB* stock over all 401 *ads*. Since the most extensive dataset from the Federal Statistical Office covering *NRB* completions spans from 1995 to 2022, completions from 1969 to 1994 were extrapolated using linear trend continuation based on the available data. Any changes in district delineation since 1995 were traced through documentation of territorial alterations and personal phone conversations with the responsible state authorities.

The outcome of the data collection pertaining to the building stock is represented by tables encompassing the number of *RBs* and *NRBs* per *cac* and building type (*bt*) for each *ad* in Germany. This represents a new and valuable resource and is provided in Supporting Table S1.

2.1.2 | Database queries: Insulation progress data

Data regarding the insulation progress of the German building stock are obtained from two separate research databases. For *RBs*, the "Datenerhebung Wohngebäudebestand 2016" (Cischinsky & Diefenbach, 2018), which translates to "data collection on *RB* stock 2016" was utilized. In this context, the Institute for Housing and Environment (IWU) gathered data from approximately 17,000 *RBs* in Germany using questionnaires, including information on insulation progress, which were partially utilized here. For *NRBs*, the IWU database "Forschungsdatenbank Nichtwohngebäude" (Scientific database *NRBs*) (Hörner, 2022) was leveraged. The database was constructed from 2015 to 2019 by using surveys specifically including the energy performance of *NRBs*. The IWU data were used for scientific analyses. Extensive database queries were made using "R-Statistics". To reflect the structure of the data researched so far, that is, *bt*, *cac*, etc., corresponding subsets were defined. Subsequently, key figures regarding the insulation progress of the respective subsets of buildings for both *RBs* and *NRBs* were queried. These include "insulation rate [%]", "share of facade area covered with ETICS [%]", "location of insulation application [categorial]", "thickness of insulation layer [m]", and "insulation at time of construction (as opposed to retroactive insulation) [%]". Detailed information regarding the insulation parameters as well as external wall surfaces employed in this study is made available in Supporting Table S2.

2.1.3 | Market data: EPS in ETICS

To derive EPS masses from ETICS volumes, the market share of EPS in the market for ETICS, as well as the bulk density of EPS, is required. The market share was calculated using market data on installed ETICS areas for various insulation materials from the German Association for Insulation Systems Render and Mortar VDPM (Schwitalla et al., 2023). Historic market shares of EPS in ETICS fluctuate around 85%. However, a significant decrease in the usage of EPS for external wall insulation in favor of mineral wool and wood fiberboard insulation panels can be observed over the past 10 years. This leads to an average market share of 79.32% for EPS insulation between 1977 and 2023, which is the maximum timespan provided by the VDPM.

As for the bulk density of EPS, literature values show great dispersion, ranging from 15 kg/m^3 (Albrecht & Schwitalla, 2015) up to 30 kg/m^3 (Institut Bauen und Umwelt e.V., 2022). To allow for comparisons of this bottom-up analysis to the installation statistic from the VDPM, an average EPS density of 25 kg/m^3 was chosen as a baseline value, as assumed by the VDPM ("baseline-25"). However, it is noted that 25 kg/m^3 is at the upper end of the density range and that an EPS bulk density of 15–20 kg/m^3 appears to be a more accurate average for application in ETICS in the German building stock (Heller & Flamme, 2020; Heller & Flamme, 2017; Schleier et al., 2022) as was additionally confirmed through expert judgments. Therefore, a second baseline scenario with an EPS bulk density of 20 kg/m^3 is introduced ("baseline-20"), leading to two baseline scenarios "baseline-25" and "baseline-20." While no separate baseline scenario is defined for a density of 15 kg/m^3, results for this density are also presented in the analysis for completeness. To explore the full range of potential EPS densities, the "min-possible" and "max-possible" scenarios in the scenario analysis (Section 3.3), systematically alter all model parameters, including EPS density, across a broader spectrum.

2.1.4 | Survey: ETICS lifetimes

The average lifetime of ETICS directly affects the point in time when waste masses occur and therefore is a critical parameter for waste quantification and forecast. However, literature values show considerable variability, ranging from 21 years (Tavares et al., 2020), up to 65 years (Lindner et al., 2020). To address this considerable uncertainty regarding lifetimes, an own survey on the lifespan of EPS-based ETICS was conducted among stakeholders from industry and research. As part of the survey, stakeholders from practice, that is, architects, building experts, engineers, ETICS certifiers, government officials, ETICS manufacturers, and plasterers, as well as experts from academia were interviewed. As part of the survey, participants were prompted to offer their evaluations concerning the lifespans of EPS-based ETICS, specifying a minimum, maximum, and most probable value for each assessment. Out of the total 75 responses, 64 individuals specified a "most-likely" value, 40 specified a "minimum" value, and 42 specified a "maximum" value. The average "most likely" value was 40 years, with average minimum and maximum values of 25 and 55 years. An overview of the responses of different stakeholder groups is shown in the supporting information (S-3).

2.2 | Data processing and calculation

For the calculation of installed ETICS volume in Germany on the NUTS-3 level of detail, the total external wall surface is multiplied by the ETICS insulation progress, for $t = 2022$. The first part consists of the number of buildings per administrative district *(ad)*, construction age class *(cac)*, building category *(bc)*, and building type *(bt)*, which is multiplied by the typological external wall surface area per building for each *cac*, *bc*, and *bt*. The sum overall *ad*, *cac*, *bc*, and *bt* provides the total external wall surface of the building stock in Germany.

The ETICS insulation progress is the product of the ETICS insulation rate, the share of facade area covered with ETICS for *cac*, *bc*, and *bt*, the share of insulation mounted on the outside of the wall—as opposed to an installation within the interior space or cavity insulation of the wall—and the thickness of the external insulation layer for each *cac* and *bc*. This results in the relative share of insulated exterior facades in the building stock.

Finally, the mass of EPS-based ETICS installed between 1969 and 2022 in the German building stock is calculated by multiplying ETICS volume with the market share of EPS in ETICS and the bulk density of EPS. Figure 2 visualizes the calculation. Since the number of buildings is given at

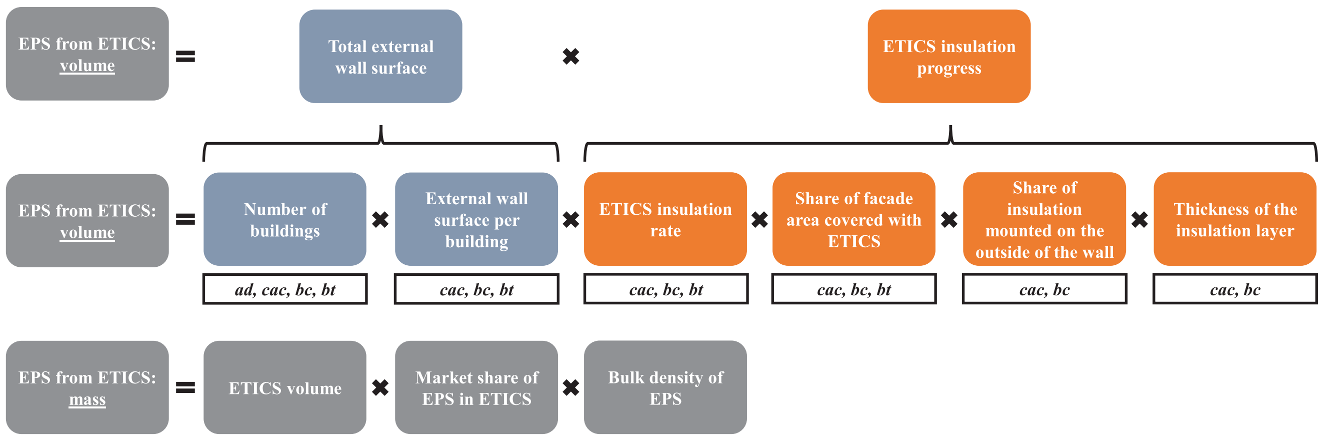


FIGURE 2 Graphical representation of the structure of the formulated equations with variables and associated indices: administrative district: *ad* ϵ {1,…,401}, construction age class: *cac* ϵ {…–1919; 1919–1948; 1949–1957; 1958–1968; 1969–1978; 1979–1983; 1984–1994; 1995–2001; 2002–2009; 2010–2022}, building category: *bc* ϵ {*RB*, *NRB*}, building type: *bt* ϵ {*SFH*, *TH*, *MFH*, *LMH*} for *RB*s, and *bt* ϵ {*PB*, *SB*} for *NRB*s. *ad*, administrative district; *cac*, construction age class; *bc*, building category; *bt*, building type; EPS, expanded polystyrene; ETICS, external thermal insulation composite system; *NRB*, non-residential buildings; *RB*, residential building; *SB*, service buildings; *PB*, production buildings; *SFH*, single-family house; *TH*, terraced house; *MFH*, multi-family house; *LMH*, large multi-family house.

NUTS-3 *ad* level for all *bcs* and all *bts*, the resulting installed EPS-ETICS masses also have a NUTS-3 level of detail. This means that the newly installed annual masses can be specified for each *ad*, *bc*, and *bt*. This is very helpful for localized future projections on EPS waste from ETICS.

2.3 | Sampling and forecasting

For future analyses, such as the design and optimization of ETICS recycling networks, it is insufficient to solely possess information regarding the timing and locations of ETICS installations. Rather, it is crucial to determine the point at which they transform into waste. Therefore, a prediction of the expected lifetime and the resulting timing of waste generation is conducted. To achieve this, the timing of insulation installation is determined as a first step. It is explicitly noted that the construction year of a building does not necessarily correspond to the timing of insulation installation. This is because older buildings, in particular, were often insulated retroactively. This is evidenced by the fact that nearly half of the German building stock relevant to the GEG was constructed before 1970, a time when external wall insulation via ETICS was neither regulated nor widespread. However, according to the data queried from the IWU databases, these older buildings are insulated to 40% on average due to retrofits. To account for this factor, information regarding the insulation timing is queried from the aforementioned databases for each *cac*. The structure of the database allows for a separation of buildings into two subsets: (a) buildings insulated at the time of construction and (b) buildings insulated retroactively.

For each building in subset (a), the year of construction is drawn from a uniform distribution of years in the respective *cac*. For retroactively insulated buildings (subset b), the year of insulation is drawn from a probability distribution utilizing EPS-ETICS installation statistics provided by the VDPM (Schwitalla et al., 2023) and logical reasoning. As retroactive fitting within the *cac* of the respective building is highly unlikely due to long retrofit cycles in the building sector, the year of insulation is drawn from all years starting with the *cac* immediately following the building's original *cac*. After determining the year of insulation for each building, an expected ETICS lifetime is determined for each building individually. The expected lifetime is drawn from the probability function of lifetimes generated by the survey (Section 2.1.4). As the survey asked participants to state a minimum, maximum, and most likely lifetime, a triangular distribution of ETICS lifetimes is chosen, as it is defined by exactly these three parameters. Subsequently, for each building, an ETICS lifetime is drawn from the triangular distribution and added to the year of insulation to derive the simulated occurrence time of the masses as waste. All calculations were performed using "Python 3.12.3.". Even with individual sampling on the single-house level for over 20 million houses, the runtime for sampling and forecasting was shorter than 1 min.

3 | RESULTS

3.1 | ETICS installations between 1969 and 2022 and their distribution across the German building stock

According to the presented bottom-up method, the calculations comprise a total area of 1.49 billion m^2 of ETICS installed in Germany between 1969 and 2022. 1969 is chosen as the starting point of the analysis as it marks the beginning of the first *cac* relevant for ETICS installations in

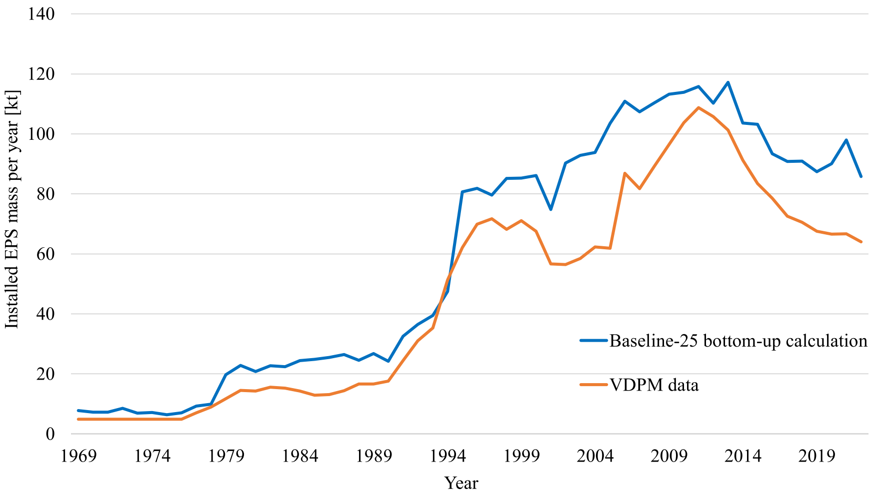


FIGURE 3 Temporal evolution of installed expanded polystyrene (EPS) masses in external thermal insulation composite systems (ETICS), comparison of VDPM statistic (Schwitalla et al., 2023) with a bottom-up result for the baseline-25 scenario. Underlying data for this figure are available in Supporting Table S3.

Germany. The corresponding volume of ETICS insulation material installed during the same period amounts to 162 million m^3 resulting in an average insulation layer thickness of 10.9 cm for the German building stock calculated from individual, *cac*-specific insulation layer thicknesses in the baseline scenarios. The associated mass calculates to 3213 kt of EPS in ETICS assuming a bulk density of 25 kg/m^3 (baseline-25) and 2571 kt assuming a density of 20 kg/m^3 (baseline-20). This is comparable to the values reported by VDPM (Schwitalla et al., 2023), which fall within similar magnitudes: 1.39 billion m^2 of installed ETICS area, 132 million m^3 of installed ETICS insulation layer volume, and 2513 kt of EPS mass from ETICS installed between 1969 and 2022, assuming a bulk density of 25 kg/m^3.

For the baseline-25 scenario, the resulting mass of EPS-based ETICS in the presented bottom-up approach is 28% higher than stated by the VDPM. This can be attributed to a 7% higher installed ETICS area and the subsequent increase of ETICS volume by 23%, mainly due to a higher average insulation thickness in the bottom-up calculation compared to VDPM. The *cac*-specific insulation thicknesses utilized for the bottom-up calculations can be found in Supporting Table S2. For the baseline-20 scenario, the calculated tonnage matches the VDPM statistic.

Additionally, results for an EPS bulk density of 15 kg/m^3 are provided for comparison. With this density, the total mass of EPS in ETICS is calculated to be 1928 kt, which represents a 25% reduction compared to the baseline-20 scenario. This reduction is directly proportional to the change in density.

The high precision of the bottom-up analysis in the baseline scenarios compared to VDPM statistics pertains to both the absolute results as well as the temporal distribution. A comparison of the installation statistic of the VDPM with the time series of the bottom-up calculated installed EPS-based ETICS insulation layer masses in the baseline-25 scenario (Figure 3) shows that the bottom-up calculation accurately reflects the temporal progression of the installed masses. Upon closer inspection, three increases can be observed: The first corresponds to the introduction of the initial Thermal Insulation Regulation in Germany in 1977 ("WärmeSchutzVerordnung"), while the second occurred in the early 1990s following the German reunification and the subsequent insulation of buildings in former East Germany. Furthermore, stricter government regulations, such as the Energy Saving Ordinance ("EnEV 2002") and its amendment ("EnEV 2009") coincide with the observable increase of the late 2000s. Finally, the recent decline of installed EPS mass in ETICS can be attributed, in part, to the decreasing market share of EPS in the ETICS market in favor of mineral wool and sustainable alternatives such as wood fiber insulation (Albrecht & Schwitalla, 2015).

In addition to aggregated metrics for the overall German building stock, the presented bottom-up approach provides insight into the distribution of insulation masses across building classes, that is, *RBs* and *NRBs*, as well as *bts* including *SFHs*, *THs*, *MFHs*, *LMHs*, *PBs*, and *SBs*, unlike the VDPM production statistic. Additionally, the insulation masses can be allocated to the introduced *cacs*. Out of the 3214 kt of EPS mass from ETICS in the baseline-25 scenario, 79% is attributed to *RBs* and 21% to non-*NRBs*. The breakdown of the masses for each *bt* and *cac* can be found in the supporting information (S-3). The majority of EPS masses are attributed to *SFHs* and *MFHs*, while *THs* and *LMHs* play a relatively minor role among *RBs*. Of the EPS mass from ETICS of *NRBs*, 59% is allocated to service buildings and 41% to production buildings. Regarding the distribution of masses across *cacs*, it can be noted that newer building age classes constitute a large proportion of the EPS from ETICS masses, while the *cac* from 1958 to 1968 also shows high values. The decline in 1979–1983 can primarily be attributed to the short length of the *cac*.

3.2 | Prediction of future EPS waste from ETICS and total ETICS deconstruction waste

Based on the calculated installed EPS masses from ETICS, future projections of EPS waste from ETICS were derived by sampling lifespans on the single building level for each year and *ad* individually for the baseline scenarios. The additional scenarios "min-possible" and "max-possible" are defined by systematic adjustment of the input variables derived from databases by their associated standard errors. Additionally, assumptions

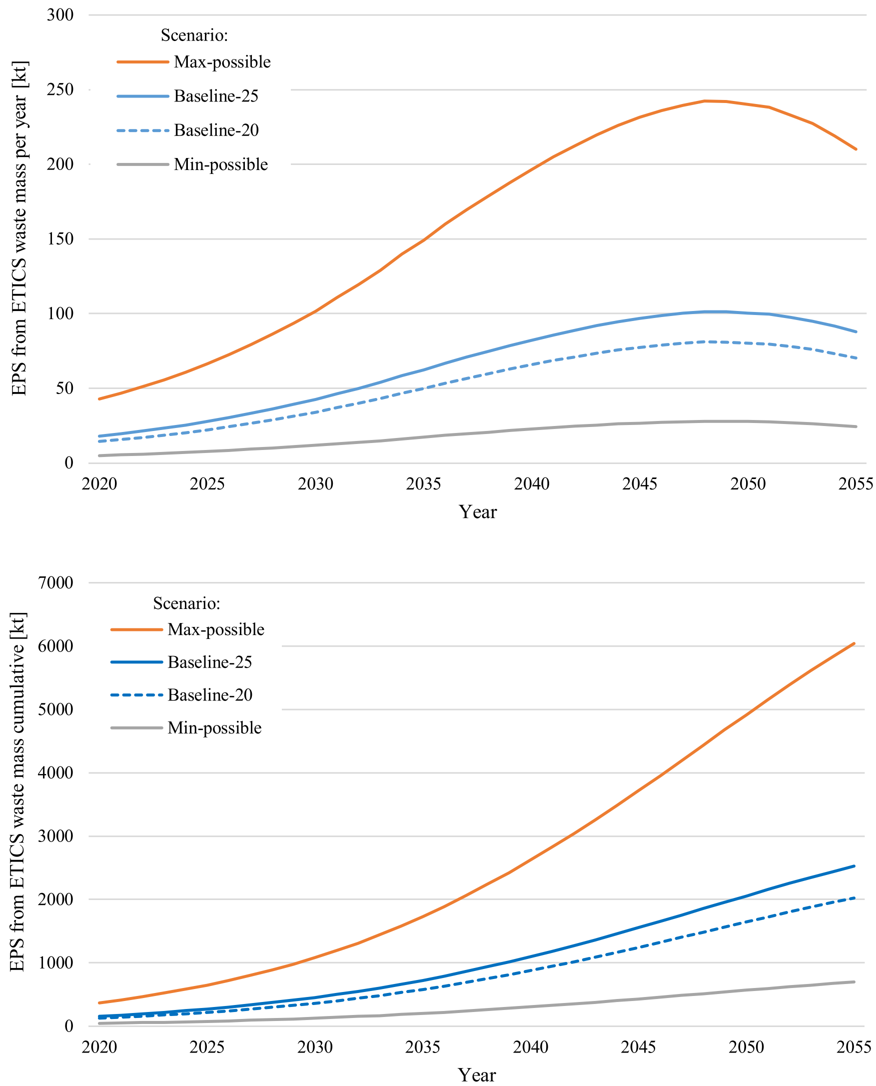


FIGURE 4 Predicted expanded polystyrene (EPS) from external thermal insulation composite systems (ETICS) waste per year (top) and cumulative (bottom): max-possible, baseline-25, baseline-20, and min-possible scenario. Underlying data for this figure are available in Supporting Table S4.

regarding the EPS market share and the bulk density of the insulation material were varied. See Section 3.3 for a more detailed description of the scenarios. The resulting projection extends over a span of 30 years into the future (until 2055) and may serve as a foundational framework for future investigations. A 30-year period was chosen as it lies significantly below the expected lifespan of ETICS of 40 years. This allows for avoiding assumptions about future quantities of installed EPS-based ETICS. Based on the projected waste generation for Germany as a whole (Figure 4), it becomes evident that we are currently observing the initial stages of an upward trend. The annual waste volumes are expected to quadruple in the baseline scenarios compared to current levels, reaching a plateau of approximately 100 kt of EPS insulation waste around 2048 for the baseline-25 scenario. This will inevitably lead to further exacerbation of the current waste disposal issue for EPS from ETICS. For more information regarding the defined scenarios, refer to Section 3.3. The observable decrease in annual EPS waste quantities following the plateau in 2048 depicted in the graph is partly attributable to the declining market share of EPS within the ETICS market observed over recent years, decreasing from 85% in 2013 to 54% in 2023 (Schwitalla et al., 2023). ETICS installations carried out between 2013 and 2023—with a declining market share of EPS—are nearing the end of their useful life starting around 2050, contributing to the observable dip in waste quantities.

It should be explicitly noted that the presented figures solely pertain to the mass of the EPS insulation layer, not the mass of the actual resulting ETICS deconstruction waste. In practice, however, contamination of EPS waste from ETICS occurs due to its application in composite systems and demolition practices in the construction industry (Heller & Flamme, 2020). The total mass of ETICS waste can be roughly estimated by utilizing the mass share of EPS in the composite system. However, this mass fraction is influenced by a multitude of factors, such as the type and thickness of the EPS insulation layer, as well as the structure of the surrounding composite system. Accordingly, literature values demonstrate a high variance ranging from 8.85 to 19.20wt% (Michalak, 2021; Schwitalla et al., 2023; Verband für Dämmsysteme, Putz und Mörtel e.V., 2017). Despite these uncertainties, an average mass share of 10wt% EPS in ETICS is commonly assumed for the German building stock, as noted by Heller and Flamme (2020). Applying this 10wt% average, the ETICS deconstruction waste mass in Germany is projected to reach a cumulative amount of 18.3 Mt from 2025 to 2055 under the baseline-20 scenario and 22.8 Mt under the baseline-25 scenario. The maximum annual ETICS deconstruction waste is

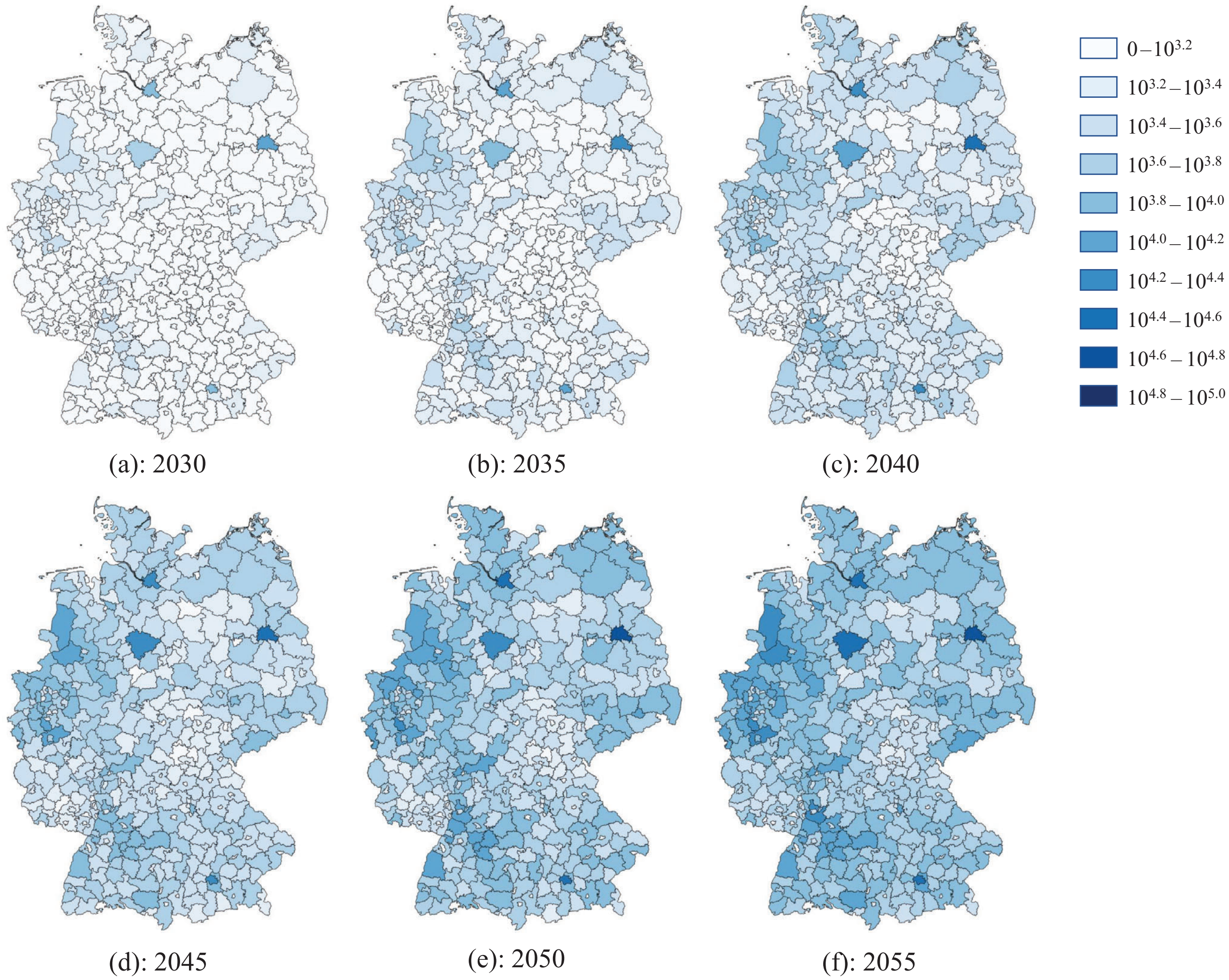


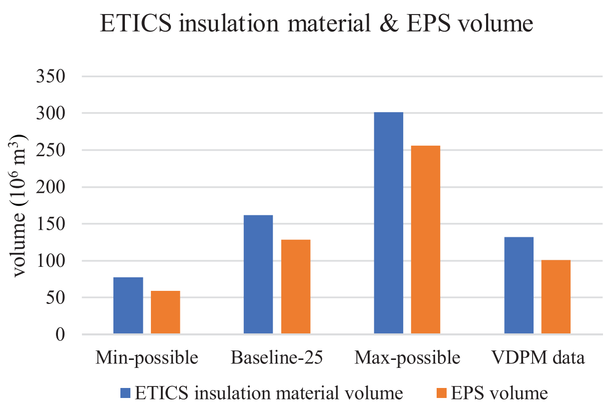
FIGURE 5 Projected cumulative expanded polystyrene (EPS) from external thermal insulation composite systems (ETICS) waste mass (t) in the years (a) 2030, (b) 2035, (c) 2040, (d) 2045, (e) 2050, and (f) 2055 for the baseline-25 scenario. Underlying data for this figure are available in Supporting Table S5.

expected to peak in 2048 at 810 kt/a for baseline-20 and 1013 kt/a for baseline-25. In addition to the aggregated results, the presented bottom-up approach allows for inferences regarding the spatial distribution of installed ETICS masses. Consequently, the prediction of resulting cumulative waste masses at the NUTS-3 level of detail is feasible. The outcomes for the baseline-25 scenario are visualized in the form of heat maps (Figure 5) where darker districts have a higher expected cumulated EPS from ETICS waste.

The maps clearly show that accumulated EPS masses from ETICS concentrate in large metropolitan regions like Berlin, Hamburg, Munich, and the Hannover region. Additionally, an increased concentration can be observed for North Rhine-Westphalia, Western Lower Saxony, and the Upper Rhine and Neckar region.

3.3 | Sensitivity and scenario analyses

As the calculation model for EPS waste volumes from ETICS and their respective masses is characterized by independent linear factors, an increase of any of the factors by a certain amount will lead to a proportional increase of the product by said amount. Therefore, a sensitivity analysis of the calculation is trivial. However, to account for the data's underlying uncertainty, a scenario analysis is performed. In addition to the baseline scenarios, a max-possible and min-possible scenario are introduced to explore the range of possible future waste volumes. Therefore, insulation progress, that is, values for insulation rate, the thickness of the insulation layer, the share of insulation mounted on the outside of the walls, as well as the ratio of insulated surface area to total facade area, are associated with relative standard errors (SEs). To create the min-possible and



Baseline-25 Comparison				
	Min	Baseline-25 (Baseline-20)	Max	VDPM data
ETICS surface area (m^2)	62%	100%	151%	94%
ETICS insulation volume (m^3)	48%	100%	186%	81%
EPS in ETICS volume (m^3)	46%	100%	198%	78%
EPS in ETICS mass (t)	28%	100% (80%)	239%	78%

FIGURE 6 Scenario analysis results for the baseline-25, min-possible and max-possible scenarios (left) and comparison to the baseline-25 scenario (right). Underlying data for this figure are available in Supporting Table S6. EPS, expanded polystyrene; ETICS, external thermal insulation composite systems.

max-possible scenarios, each baseline value is modified for each variable in the following way:

$$Max - possible: \ Base\,linevalue \times (1 + relative\ SE)$$

$$Min - possible: \ Base\,linevalue \times (1 - relative\ SE)$$

Moreover, it is crucial to acknowledge the limited availability of representative data concerning external wall surface areas for the designated *bts*. To address this scarcity, it is postulated that the wall surface area for each *bt* may deviate by up to 10% from the values stated in the building typology. This adjustment is made to ensure a more comprehensive consideration of potential variations in the external surface area across different *bts*. In addition, values that are specific to the insulation material EPS, like market share and EPS bulk density, are modified for the scenario analysis as follows. The lower bound for the EPS market share for ETICS application is 76%, taken from the German Federal Environment Agency (Schöpel et al., 2018), while 85% acts as an upper bound, derived from annual maximum values (Schwitalla et al., 2023). In terms of density, literature values exhibit considerable dispersion, spanning from 15 kg/m^3 (Albrecht & Schwitalla, 2015) up to 30 kg/m^3 in EPDs (Institut Bauen und Umwelt e.V., 2022). To comprehensively address this variability, the incorporated min-possible and max-possible scenarios encapsulate the range of densities previously described. This approach ensures that the assessment encompasses the full spectrum of density possibilities, allowing for a robust evaluation of the system's performance under varying density assumptions. The aggregated results for the different scenarios as well as the comparison to the baseline scenario can be observed in Figure 6.

As shown in Figure 6, the min-possible and max-possible scenarios regarding the ETICS surface area result in 62% and 151% of baseline surface area. The spread of scenarios increases as more variables are varied; for example, from surface area to ETICS volume, average insulation thickness per *bc* and *cac* is additionally taken into account. For the EPS volumes in ETICS, the market share of EPS is additionally considered. The greatest variability exists in terms of the mass of EPS insulation materials in ETICS, attributed to the wide range of possible EPS bulk densities ranging from 15 to 30 kg/m^3.

4 | DISCUSSION

4.1 | Data limitations

The results of the bottom-up quantification for EPS from ETICS are supported by data from VDPM statistics, both in absolute terms and over time. This statistical support adds credibility to the findings of this study and enhances their reliability. The bottom-up methodology employed in this study is not reliant on industry-reported production or installation statistics, eliminating potential biases. Additionally, this methodology is transferable to other European countries. Even if aggregated production statistics are not available, the methodology is applicable since the employed building typology covers many European nations. However, additional data generation regarding the insulation progress of the building stock, that is, insulation rates and thicknesses, is required for countries where such information is not readily available and therefore cannot be queried. Furthermore, data limitations include restrictions in data granularity which arose during database queries. This was due to subsets becoming too small for meaningful analysis if queries were excessively granular. Second, potential standard errors inherent to the database queries were recognized. To address this concern, a scenario analysis was conducted to make the underlying standard errors transparent. Finally, data regarding the German *NRB* stock are not available at the NUTS-3 level of detail. To address this limitation, construction completion statistics for *NRBs* from the German Federal Statistical Office were utilized. These statistics are provided at the NUTS-3 level. However, they do not cover every year within the analysis period, necessitating extrapolation to fill in the gaps.

4.2 | Methodological limitations

The bottom-up methodology used in this study provides detailed insights into the distribution of insulation masses among different building classes (i.e., *RB*s and *NRB*s) and their subtypes, as well as various building age classes. This granularity facilitates an improved understanding of insulation usage in the German building stock. Lifespan data used in the analysis are derived from a survey conducted with various stakeholders, accounting for diverse perspectives within the industry and academia in Germany. Furthermore, the study offers insights into the local distribution of generated waste streams at the NUTS-3 level. This information serves as a valuable basis for designing future recycling networks and optimizing recycling strategies, contributing to sustainability efforts in the construction sector. However, the results of this study only pertain to EPS waste from ETICS. Other sources of EPS waste in the construction sector, like pipe insulation made of EPS or impact sound insulation in the flooring, are not considered.

Lifespan data used in the analysis are derived from a survey conducted with various stakeholders to account for diverse perspectives within industry and academia in Germany. However, as the lifetime survey was conducted with German stakeholders only, its results pertain to the German building stock. Accordingly, survey results may deviate for countries with different climatic conditions.

4.3 | Recommendations for future research and waste management policies

The presented approach employed archetypal external wall surfaces from exemplary buildings as defined in the employed TABULA building typology. However, it is acknowledged that more representative external wall surface areas derived from large-scale surveys would further enhance the accuracy of the analysis. Looking forward, the release of more representative building data by IWU is anticipated for 2025. This information was obtained directly from IWU through personal conversations. This planned update will incorporate more precise exterior wall area measurements, thereby improving the accuracy of future estimations based on this parameter.

The lack of centralized documentation for ETICS installations in the past has resulted in an insufficient data foundation, which was addressed by this study. However, this issue extends to the building sector in general. A centralized database, maintained by statistical offices, documenting all installed construction materials, including insulation, would improve the situation. Recent efforts in Germany like "Madaster," an online material cadastre that generates and registers material passports for the building sector (Heisel & Rau-Oberhuber, 2020), may serve as a valuable resource if freely available and should be developed further.

In addition to insufficient building data availability, conventional ETICS design and installation practices, together with current building deconstruction methods, pose a challenge to the effective recycling of ETICS. Non-selective dismantling of building facades leads to large amounts of unseparated waste, which hinders effective ETICS waste treatment. Selective dismantling—that is, scraping off the insulation layer by hand or by excavator—should be the preferred option for ETICS, either enforced through legal mandates or by regulatory cost increases for mixed construction waste disposal (Reinhardt et al., 2022). The resulting segregated ETICS waste stream should be collected separately and prepared for further recycling steps by separating the EPS insulation layer from the mineral fraction and other ETICS components and optionally compacting the EPS fraction for transport.

As an alternative to the status quo of energy recovery in MSWIs, the EPS fraction of ETICS can be recycled through the "PolyStyreneLoop." This solvent-based approach developed by Fraunhofer allows for the recovery of Polystyrene and the removal of contaminants such as HBCD (Demacsek et al., 2019). This approach yields both economic and environmental benefits over the current status quo (Schleier & Walther, 2024; TÜV Rheinland LGA Products GmbH, Germany, 2019). Currently, one demonstration plant is under operation in Terneuzen, Netherlands. However, as annual capacity of the demonstration plant is limited to 3000 tons of EPS waste per year, or approx. 3% of predicted peak annual EPS from ETICS waste generation under baseline-25 or 3.7% under baseline-20 in 2048, this approach alone is insufficient (European Commission, 2019). Furthermore, only the EPS fraction of ETICS, that is, 10wt% of total ETICS mass (Heller & Flamme, 2020), can be recycled through the PolyStyreneLoop. To effectively address the predicted growing waste volume and the limitations of recycling only the EPS fraction, this process must be scaled up and supplemented by alternative recycling pathways.

Joint utilization of both the organic and mineral fractions could be achieved through co-firing in cement clinker plants, where the EPS fraction is used to substitute conventional fuels like lignite, while the mineral-rich combustion ashes are transferred into the cement clinker (Heller & Flamme, 2020). Other approaches, such as chemical recycling of the organic fraction through pyrolysis and the use of the mineral fraction for cement clinker production, are currently under investigation. The success of such alternative recycling pathways could be significantly influenced by the legal framework. Policy measures, such as legal recycling quotas for ETICS, could stimulate the development of suitable recycling processes. Furthermore, recycling obligations and take-back requirements for ETICS manufacturers could facilitate reverse logistics and enhance recyclability through appropriate design. The effectiveness of these measures also depends on factors such as transport, processing, and disposal costs, warranting further investigation.

5 | CONCLUSION

This study introduces a novel approach to determine the amount of ETICS installed in the German building stock, in particular with EPS as the insulation layer, and projects the future ETICS waste generation expected through 2055. The bottom-up nature of the approach makes it independent of industry data and provides a high level of detail, entailing NUTS-3 localization of ETICS masses for *RBs* and *NRBs*, for different *bts* and *cacs*, filling critical knowledge gaps. High granularity and independence from industry data are achieved via extensive research database queries and subsequent data processing. Waste stream predictions for EPS from ETICS are conducted through probabilistic lifetime sampling on a single-house level, utilizing lifetime survey results from diverse stakeholder groups within industry and academia. The waste prediction results, analyzed at the NUTS-3 level of detail, project a fourfold increase in annual EPS waste mass from ETICS compared to current levels. This anticipated surge in waste volume suggests that existing disposal routes are inadequate, underscoring the urgent need for alternative recycling pathways and enhanced waste management policies. As the construction industry moves toward more sustainable practices, these findings provide a critical foundation for advancing ETICS recycling efforts. Specifically, they can inform the design of reverse logistics networks and guide both policymakers and industry leaders in developing more efficient, circular waste management systems.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are made available in the Supporting Information

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author used “OpenAI ChatGPT” and “Microsoft Copilot” to improve the formulation of English text. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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