A Framework for Exergetic Life Cycle Assessment of Residential Buildings

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Abstract

This thesis develops a framework for integrating exergy analysis into Life Cycle Assessment (LCA) applied to residential buildings. The central research question addresses whether, from an exergy perspective encompassing both resource use and emissions, it is more sustainable to renovate an existing residential building or to construct a new one using improved materials and low-emission heating systems.

The study employs a multi-dimensional exergy-based assessment approach, quantifying three primary categories: (1) Resource Exergy Consumption of Energy (RExC-E), calculated using Resource Exergy Analysis (REA); (2) Cumulative Exergy Consumption including Chemical Exergy Consumption of Materials (CExC-M) derived from standard chemical exergy values and Primary Exergy Consumption of Energy (PExC-E) for construction materials, ;and (3) Chemical Exergy of Emissions (CExE) for environmental outputs. This integrated framework provides a unified thermodynamic basis for evaluating both resource depletion and environmental emissions.

The methodology is demonstrated through a case study of a representative 1999 German multi-family row house (Neu-Ulm), comparing three fundamentally different scenarios over a 50-year period (2025–2075): (1) the original building in its existing state; (2) a renovated scenario with thermal envelope improvements and renewable heating; and (3) a new-build scenario with advanced components, timber structure, and efficient systems.

Key findings indicate that the renovated scenario yields the lowest Overall Exergy Impact, demonstrating that upgrading heating systems and building envelopes before the end of a building's service life can substantially reduce environmental impacts. The new-build scenario, despite improvements in operational energy, exhibits higher total exergy due to substantial material burdens from new construction. Sensitivity analysis reveals that strategic decisions regarding material reuse—such as retaining the original foundation—can significantly improve the environmental performance of new construction.

The study demonstrates that exergy-based LCA can provide robust thermodynamic foundations for sustainability assessment, offering advantages over conventional LCA by incorporating energy quality and enabling unified comparison of resource consumption and emissions. However, limitations remain regarding methodological consistency. The research supports renovation as the most effective strategy for minimizing exergetic and environmental impacts in building stock interventions, while highlighting the critical importance of methodological transparency and scope definition in exergy-based assessments.

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All interpretations, conclusions, and methodological decisions presented in this thesis remain the sole responsibility of the author.

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Acronyms

A1	Raw material extraction (LCA stage)
AI	Artificial Intelligence
A/C	Air conditioning
ADP	Abiotic Depletion Potential
ADP elem.	Abiotic Depletion Potential - Elements
AExA	Exergoenvironmental Analysis
AGFW	Arbeitsgemeinschaft Fernwärme
AP	Acidification Potential
BBSR	Bundesinstitut für Bau-, Stadt- und Raumforschung (Federal Institute for Research on Building, Urban Affairs and Spatial Development — Germany)
BIM	Building Information Modeling
BNB	Bewertungssystem Nachhaltiges Bauen (Sustainable Building Assessment System — Germany)
C4	End-of-life/Disposal (LCA stage)
CED	Cumulative Energy Demand
CEENE	Cumulative Exergy Extraction from the Natural Environment
CExC	Cumulative Exergy Content
CExD	Cumulative Exergy Demand
CExE	Chemical Exergy of Emissions
CFC-11	Chlorofluorocarbon-11
CH_4	Methane
CHP	Combined Heat and Power
CLT BBS	Cross-Laminated Timber (Brettsperrholz in German, engineered wood panels for construction)
CO_2	Carbon dioxide
DIN	Deutsches Institut für Normung (German Institute for Standardization)
ECA	Energy Concept Adviser
ECExD	Ecological Cumulative Exergy Demand
EEA	Extended Exergy Accounting
EExA	Extended Exergy Analysis
ELCA	Exergetic Life Cycle Assessment
eLCA	Online tool for environmental life cycle assessment (Bauteileditor)
EM	Emission Mass
EmA	Emergy Analysis
EN	Europäische Norm (European Standard)
EN 15804	European Standard for Environmental Product Declaration
EnEV	Energieeinsparverordnung (German Energy Saving Ordinance)
EP	Eutrophication Potential
EPDM	Ethylene Propylene Diene Monomer
Ex_b	Specific exergy
ExLE	Exergy of Life cycle Emissions
GaBi	Ganzheitliche Bilanzierung (LCA software)
GWP	Global Warming Potential
HVAC	Heating, Ventilation, and Air Conditioning
IBP	Institut für Bauphysik (Fraunhofer Institute for Building Physics, Germany)
ICExD	Industrial Cumulative Exergy Demand
IEA ECBCS	International Energy Agency — Energy Conservation in Buildings and Community Systems
KfW	Kreditanstalt für Wiederaufbau
kg	kilogram
kJ	kilojoule
KVH	Konstruktionsvollholz (solid structural timber used in construction)
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
LCA	Life Cycle Assessment
LED	Light-Emitting Diode

LHV	Lower Heating Value
LowEx	Low-Exergy
MExD	Material Exergy Demand
MJ	Megajoule
MM	Material Mass
N_2O	Nitrous Oxide
NO_X	Nitrogen Oxide
NPP	Net Primary Productivity
ODP	Ozone Depletion Potential
OExI	Overall Exergy Impact
OSB	Oriented Strand Board
PA	Polyamide
PE	Primary Energy
PEC	Primary Energy Consumption
PED	Primary Energy Demand
PERE	Primary Renewable Energy
PENRE	Primary Non-Renewable Energy
PExD	Primary Exergy Demand
PO_4^{3-}	Phosphate ion
POCP	Photochemical Ozone Creation Potential
REAP	Resource Efficiency in Architecture and Planning
REA	Resource Exergy Analysis
Sb	Antimony
SCExE	Standard Chemical Exergy of the Emission
SCExM	Standard Chemical Exergy of the Material
SO_2	Sulfur dioxide
TEC	Thermo-Ecological Cost
U-value	Thermal transmittance value
W/m^2K	Watts per square meter per Kelvin
Zero-ELCA	Zero emission exergetic life cycle assessment

1. Introduction

1.1. The History of Exergy

The concept of exergy emerged from pioneering work in thermodynamics during the nineteenth and twentieth centuries. Scientists investigated the ability to perform useful work as a measure of energy quality. The formal term "exergy" was coined by Zoran Rant in 1956, marking the beginning of exergy as a recognized branch of thermodynamics. This concept built upon earlier terminology such as "available energy" and "availability," which had been used to describe similar notions. The mid-twentieth century saw the application of exergy analysis expand from theoretical considerations to practical engineering, particularly in the analysis of thermal systems and energy conversion machinery, where it was employed to quantify and minimize energy flows that failed to generate useful work and to optimize system performance and efficiency [1][2]. The term "exergy" integrates the First Law of Thermodynamics, energy conservation, and the Second Law, entropy generation. This combination allows for the quantification of the maximum useful work that a system can perform while interacting with its surrounding environment [1][3].

Unlike traditional energy analysis, which only accounts for the quantity of energy, exergy analysis incorporates both the quantity and quality of energy. It measures the deviation of a system from its environmental equilibrium and defines the potential of the system to perform work. In this framework, when a system reaches thermodynamic equilibrium with its environment, it has no capacity to do work and, therefore, possesses zero exergy [1]. As a system progresses toward equilibrium, a portion of its energy can be converted into useful work, while the rest is irreversibly dispersed as heat at the temperature of the surroundings, generating entropy. In exergy terms, this implies exergy destruction [1][2].

The distinction between energy quality as a factor in exergy is critical in thermodynamic analysis, particularly in systems where energy is utilized at varying levels of quality. While global efforts to reduce energy consumption have yielded partial success, they often overlook the significant losses associated with exergy destruction that is not accompanied by energy losses to the surroundings – such as hot combustion, heat transfer, mixing and throttling. Incorporating exergy analysis into system assessments provides deeper insights into the rational utilization of energy and material resources and the true potential for minimizing environmental impacts [4].

By definition, exergy is the maximum theoretical work that can be extracted from a combined system comprising the system under study and its environment, as the system transitions from a given state to thermodynamic equilibrium with that environment through an ideal process

[3]. More specifically, it refers to the work potential of an energy flow or system at a certain state when it undergoes an ideal, reversible process toward the so-called "dead state", a state of thermodynamic equilibrium with its environment. Generally, the further the system's temperature deviates from the environmental baseline, the higher its exergy content, thus reinforcing the notion that exergy considers energy quantity and energy quality [5][6].

Traditional energy analysis, although widely used, is often insufficient for evaluating system performance, particularly when systems operate at various energy quality levels– such as built environments. Such analyses can be misleading when ranking systems because they fail to indicate how closely a system approximates ideal thermodynamic behavior. Exergy analysis overcomes this limitation by integrating both the First and Second Laws of Thermodynamics. It acknowledges that while energy cannot be created or destroyed, its capacity to perform work, its quality, can degrade until equilibrium with the environment is reached [7][8][9].

This degradation process is central to understanding efficiency comprehensively in real-world applications. While the total energy involved in any process remains constant, the amount of exergy decreases due to irreversibilities. This decline reflects a loss in energy quality, which cannot be captured by energy quantity assessments alone. Consequently, exergy analysis can uncover thermodynamic inefficiencies and identify suboptimal energy conversion pathways that conventional energy analysis would overlook [5].

In the built environment, this conceptual framework has profound implications. While current strategies emphasize the reduction of energy consumption, it is important to recognize that energy is not consumed in a strict physical sense but is transformed. In contrast, exergy is subject to destruction in irreversible processes, offering clearer guidance on how to enhance the efficiency of building systems [3]. Exergy analysis allows buildings to be viewed in relation to their environments, linking energy demands, such as heating, cooling, and ventilation, with the environmental conditions in which they occur. By doing so, it facilitates the optimal use of available resources [3].

In summary, exergy provides a more robust and insightful framework than traditional energy analysis for evaluating system performance, particularly in energy-intensive, complex sectors such as construction and building operation. It accounts for both the quantity and quality of energy, reveals sources of inefficiency comprehensively, and offers a methodologically rigorous path toward improving system design and reducing environmental impact. The incorporation of exergy principles into system analysis not only enhances technical accuracy but also supports the development of more sustainable energy strategies [1][4][5][7][8].

1.2. Exergy in Building Sector

Improving building energy performance increasingly depends not only on minimizing total energy use but also on optimizing energy quality and the efficiency of energy transformations throughout the building life cycle. Conventional strategies focus primarily on reducing energy demand, yet this approach overlooks qualitative differences among energy forms and the significant potential for waste arising from mismatches between supply quality and end-use requirements. Exergy analysis provides a comprehensive basis for evaluating both the quantity and quality of energy flows in buildings, revealing inefficiencies that conventional energy analysis cannot detect [3][10].

Buildings consume energy in two main forms: operational energy (for heating, cooling, hot water, ventilation, lighting, and equipment during use) and embodied energy (associated with material production, construction, maintenance, and demolition). Operational energy often constitutes the majority—typically 75–95%—of the total life-cycle energy demand in standard buildings. However, both operational and embodied stages can benefit from exergy-based optimization [11][12].

Exergy analysis highlights that not all energy supplied to buildings is equally useful; work and electricity represent high-quality energy forms, while low-temperature heat is of lower quality. Traditional buildings often use high-exergy fuels such as natural gas or electricity to meet low-exergy demands (e.g., space heating at near-ambient temperatures), resulting in considerable exergy destruction and avoidable environmental impacts. The Low-Exergy (Low-Ex) design [13] approach responds to this challenge by matching energy supply quality to end-use needs—leveraging renewables, waste heat, and district heating where possible to maximize overall exergy efficiency and minimize losses.

Exergy analysis in buildings provides several key advantages that distinguish it from conventional energy assessment. First, it offers an evaluation of energy quality thus extending analysis beyond quantities of energy to examine whether the quality of each energy supply is appropriate for its corresponding demand. This approach enhances understanding of energy use by revealing the suitability of energy sources for specific building functions. Second, exergy metrics enable the systematic detection of inefficiencies, uncovering avoidable losses that often go unnoticed in standard energy assessments. By allowing for system comparison and optimization, exergy analysis makes it possible to benchmark diverse technologies, such as gas boilers, heat pumps, or solar systems, on a common exergy efficiency basis, thus supporting fair and informed evaluations. Furthermore, the localization of losses is made possible by following exergy flows and identifying points of exergy destruction throughout different building and system components, which helps prioritize areas for improvement. Finally, exergy analysis underpins a robust sustainability assessment framework by quantifying irreversibilities and providing a more accurate measure of the true environmental burden associated with building operation and construction [5][12][14].

Recent international initiatives, especially IEA ECBCS Annex 37 [13] and Annex 49 [15], have formalized exergy as a basis for guidelines and optimization in building design and operation. These efforts have shown that shifting to exergy-based analysis and Low-Ex systems can reduce the environmental and resource demand of both new buildings and renovations, supporting the transition toward more sustainable, climate-resilient built environments.

In summary, exergy analysis complements and strengthens conventional energy assessment by exposing thermodynamic inefficiencies, promoting better supply-demand matching, and supporting the rational integration of renewable energy and advanced technologies in buildings. Its implementation is increasingly regarded as essential for the next generation of sustainable building design and policy. [8][16]

1.3. Exergy in LCA

Sustainable development depends on careful consideration of how natural resources are used, the rate at which they are depleted, and their fair distribution among both current and future generations. Life Cycle Assessment (LCA) provides a systematic framework for evaluating environmental performance across all stages, from resource extraction to end-of-life disposal, encompassing spatial and temporal scales comprehensively. However, conventional energy-based LCA metrics often overlook qualitative differences among energy forms, limiting their capacity to reveal true system inefficiencies [17].

Exergy as a unifying concept transcends these limitations by quantifying energy resources based on their thermodynamic quality and their capacity to perform work. In addition, it considers scarcity of materials on a physical basis. While traditional LCA uses mass or energy quantity alone, exergy incorporates the distance from equilibrium of a substance relative to its reference environment. Higher exergy indicates greater work potential embedded in a resource. For example, concentrated copper ore contains higher exergy than dispersed ore of equal mass, as extracting the latter requires substantially more energy. This scarcity-based perspective makes exergy particularly suitable for assessing resource depletion and material flow across the entire life cycle [12][18].

Exergy serves a dual role in LCA: quantifying the thermodynamic value of resource inputs and the environmental burden of emission outputs. Both fuels and minerals possess exergy due to their chemical and compositional distinctiveness from natural baselines. Conversely, emissions discharged into the environment, such as CO_2, NO_x, and other pollutants, retain thermodynamic disequilibrium and thus possess exergy that reflects their potential to alter natural systems and cause environmental damage. Practical application involves converting energy and material quantities into exergy units using quality factors specific to each resource type. For energy, exergy equals energy content multiplied by a thermodynamic quality factor (β-value). Materials are similarly converted using their specific chemical exergy. This transformation enables a unified exergy-based balance sheet integrating energy and material flows [19][20].

Recent frameworks, notably Cumulative Exergy Demand (CExD) [21] and Exergetic Life Cycle Assessment (ELCA) [22], have operationalized exergy in LCA contexts. CExD accounts for exergy of all resource inputs, while ELCA extends this to quantify irreversibilities (exergy destruction) throughout the life cycle. These approaches address persistent challenges in LCA: comparing dissimilar environmental impacts and accounting rigorously for resource depletion on a thermodynamic basis.

1.4. Benefits of Integrating Exergy into LCA

While Life Cycle Assessment (LCA) provides a comprehensive environmental evaluation framework, it faces a persistent methodological challenge: the calculation of characterization factors in Life Cycle Impact Assessment (LCIA). These factors require complex modeling, including multimedia fate models, exposure assessments, and experimental toxicity data, introducing significant subjectivity and data dependency. Exergetic Life Cycle Assessment addresses this limitation by expressing environmental burdens through a single, thermodynamically grounded metric: exergy.

Exergetic LCA offers several key advantages over conventional LCA. First, it provides an objective environmental indicator rooted in physical laws of thermodynamics, reducing reliance on subjective weighting and normalization schemes. Second, it enables unified assessment of both resource inputs and emission outputs through a common exergy unit, making results more directly comparable and interpretable. Third, resource scarcity accounting becomes possible, recognizing that concentrated ore deposits require less exergy to process than dispersed ones, offering more accurate quantification of true resource depletion [16][23].

A critical distinction from conventional LCA is how environmental impacts are characterized. Standard LCA typically represents each impact category through a single reference substance (e.g., CO_2-equivalents for global warming or SO_2-equivalents for acidification), which may obscure contributions from other significant emissions like methane or nitrous oxide. Exergetic LCA, by contrast, incorporates all emissions based on their respective thermodynamic potentials, providing a more complete and nuanced assessment [24].

Additional benefits of Exergetic LCA include its capacity to identify inefficiencies by revealing specific processes and life cycle phases that contribute disproportionately to irreversibility, thereby enabling targeted efficiency improvements. At the system level, exergy analysis provides valuable insights by supporting identification of environmental hotspots and guiding design optimization strategies. It also enables enhanced comparability across diverse technologies and systems through equitable benchmarking on a common thermodynamic basis. Furthermore, by circumventing complex characterization factor calculations, Exergetic LCA reduces data uncertainty by avoiding the inherent limitations of modeling and exposure assessment methods used in conventional LCA [17][25].

Exergetic LCA is particularly suitable for applications requiring rigorous thermodynamic consistency, single-objective performance metrics, combined environmental-economic assessments, and cross-system comparisons, making it an attractive tool for building and sustainability evaluations.

1.5. Exergy Methods

Integrating exergy analysis into Life Cycle Assessment (LCA) represents an evolving approach to resource and environmental evaluation [26]. Over the past two decades, various methodologies have been developed, each providing distinct perspectives on thermodynamic resource accounting and efficiency assessment. This section outlines the principal exergy-based methods currently applied in life cycle contexts, their theoretical foundations, practical applications, and relative strengths and limitations.

1.5.1. Cumulative Exergy Demand (CExD) and Cumulative Exergy Content (CExC)

The foundational exergy-based resource accounting method, Cumulative Exergy Content (CExC), was introduced by Szargut as an extension and refinement of cumulative energy analysis. CExC quantifies the total exergy consumed throughout all stages of a product's production process, from raw material extraction to final output. Unlike cumulative energy methods, which neglect non-energy resources and fail to assess thermodynamic process efficiency, CExC provides a comprehensive representation of resource use quality and process performance [12][16][23].

Szargut's approach proposes that each good or service be characterized by its CExC value, calculated by summing the exergy of all inputs—including raw materials, energy carriers, and intermediate flows—used during manufacturing. Two principal calculation approaches exist: the sequential method (process analysis), which traces exergy flows backward from final production to initial extraction, and the simultaneous method, which formulates and solves exergy balance equations for all useful outputs within a system. The simultaneous method provides greater comprehensiveness by accounting for all material, semi-finished goods, and energy vectors involved, though it requires high-resolution data and may introduce greater uncertainty [12][21][23].

Cumulative Exergy Demand (CExD), formalized by Bösch [21], is conceptually equivalent to CExC and represents the total exergy of all natural resources consumed to produce a product or deliver a service. CExD improves upon Cumulative Energy Demand (CED) by incorporating both energetic resources (fossil fuels, biomass) and non-energetic materials (minerals, metals), while accounting for energy quality through exergy content. This dual consideration significantly enhances the method's capacity to reflect the true thermodynamic cost of resource use.

CExD is now widely embedded in major LCA tools and databases, particularly ecoinvent, and has become one of the most commonly applied exergy-based environmental indicators [26]. Key advantages of CExD include the fact that exergy is an intrinsic property of resources, thereby reducing subjective assumptions in characterization factor development [21].

1.5.2. Thermo-Ecological Cost (TEC)

The Thermo-Ecological Cost (TEC) method, developed by Szargut [27], evaluates cumulative consumption of non-renewable primary exergy resources, providing a resource-use indicator expressed entirely in thermodynamic (exergetic) terms rather than monetary units. This method emphasizes quantifying and minimizing depletion of non-renewable natural resources within ecological exergy frameworks, with primary focus on capturing the thermodynamic cost of resource use in systems where sustainability concerns are tightly linked to finite reserve exhaustion [27][28].

1.5.3. Cumulative Exergy Extraction from the Natural Environment (CEENE)

Cumulative Exergy Extraction from the Natural Environment (CEENE), developed by Dewulf and colleagues [29], represents a comprehensive advancement beyond CExD by incorporating the environmental burden of land use. While CExD includes both energetic resources and non-energetic materials—such as water, minerals, and metals—it omits land occupation impacts. CEENE addresses this gap by quantitatively evaluating exergy associated with energy carriers, non-energetic resources, and land use simultaneously.

Conceptually, CEENE diverges from CExD in scope: CExD measures exergy withdrawn from nature and incorporated into technological systems, whereas CEENE encompasses the total exergy deprived from the natural environment regardless of whether it enters technological systems. This distinction provides a broader perspective on resource burdens imposed by human activity. The CEENE methodology distinguishes eight resource categories: renewable resources, fossil fuels, nuclear energy, metal ores, minerals, water resources, land resources, and atmospheric resources. The method has been coupled with the ecoinvent life cycle inventory database, enabling systematic comparison of diverse products on a unified thermodynamic basis [29].

1.5.4. Industrial and Ecological Cumulative Exergy Demand (ICExD/ECExD)

The Industrial Cumulative Exergy Demand (ICExD) and Ecological Cumulative Exergy Demand (ECExD) framework extends CExD principles to broader industrial and ecological system analysis [30]. ICExD quantifies the exergy of natural resources consumed both directly and indirectly across economic sectors using thermodynamic input-output models. ECExD further incorporates exergy expended within natural ecosystems for resource generation, providing comprehensive analysis across both industrial and ecological life cycle stages [31].

This methodology employs monetary and physical input-output tables to mathematically represent economic and ecological system interactions. A key strength is the availability of macroeconomic data across sectors; however, sectoral aggregation limits resolution at individual production activity levels [31].

1.5.5. Emergy Analysis

Emergy Analysis (EmA) represents a systems-based environmental assessment approach that quantifies all products and services in terms of equivalent solar energy. Developed by Howard T. Odum at the University of Florida, emergy treats the biosphere as the ultimate source of resources and environmental services, all ultimately derived from solar radiation [12][32].

Emergy is defined as the total amount of direct and indirect solar energy required to generate a product or support a process. This approach enables comparison of diverse resources and processes on a common basis of solar energy equivalents, providing a unified metric for environmental accounting independent of market prices or technological pathways. The method employs transformity factors—the amount of solar energy required per unit of available energy—to convert physical quantities into solar emergy units [32].

1.5.6. Exergetic Life Cycle Assessment (ELCA)

Exergetic Life Cycle Assessment (ELCA) represents a methodological extension of exergy analysis to the complete life cycle of products or systems. First introduced by Cornelissen [22], ELCA adopts the structural framework of conventional LCA, particularly regarding goal and scope definition. However, the inventory analysis phase in ELCA is substantially more detailed, requiring complete mass and energy balances for each system stage prior to calculating exergy flows and performing exergy balance calculations [12][22].

The primary objective of ELCA is quantifying irreversibilities—i.e., exergy destruction—throughout the life cycle, enabling identification of stages exhibiting thermodynamic inefficiencies. This focus facilitates opportunities for improving resource use efficiency by minimizing exergy losses. ELCA can be combined with thermoeconomic analysis, integrating monetary valuation into exergy-based performance assessment.

A principal distinction of ELCA compared to conventional LCA is its focus on exergy rather than energy, allowing more accurate representation of resource quality and actual work potential of energy carriers. ELCA thus offers similar advantages over LCA as CExC does over cumulative energy methods, providing stronger thermodynamic foundations for sustainability evaluation [33].

However, ELCA inherits several limitations from conventional LCA, particularly regarding assessment of emission toxicity and environmental harm. In standard ELCA, emissions are treated as exergy losses without reflecting their ecological or health impacts. To address this limitation, Cornelissen proposed Zero-ELCA, which introduces hypothetical separation and transformation processes to nullify emission exergy, then allocates the exergy required for these processes as the environmental cost. While this approach integrates emissions into exergy frameworks, it faces challenges: (1) separation processes for many emissions (e.g., methane from gas pipelines) remain undefined, and (2) exergy costs may diverge significantly from actual toxicity, potentially distorting environmental prioritization [22][33].

ELCA applications include: (1) assessing natural resource consumption across life cycles, and (2) evaluating resource depletion with distinctions between renewable and non-renewable sources. ELCA functions independently or as a complement to conventional LCA—when combined, ELCA addresses resource depletion and thermodynamic efficiency while LCA evaluates broader impacts such as ecotoxicity, eutrophication, and global warming potential [33].

1.5.7. Extended Exergy Accounting

Extended Exergy Accounting (EEA), also termed Extended Exergy Analysis (EExA), builds upon ELCA methodological foundations by incorporating all three classical production factors—capital, labor, and materials—into a unified exergy framework. This approach quantifies exergy equivalents of economic and social inputs, enabling comprehensive resource-based valuation of products or systems [34].

EEA encompasses the complete system life cycle, including raw material extraction, construction, operation, and end-of-life phases (demolition and waste processing). Environmental externalities in EEA are conceptually aligned with Zero-ELCA: emissions and external impacts are translated into corresponding exergy costs based on hypothetical mitigation or compensation scenarios.

Sciubba [34] formalized the EEA methodology based on two central assumptions: (a) a product's cumulative exergy content equals the sum of all physical input exergies plus weighted contributions from production process exergy—extending Szargut's CExD approach—and (b) non-energetic components (labor, capital investment, environmental emissions) can be consistently expressed in exergy terms using global system balances. The second assumption represents EEA's primary conceptual innovation. Exergy equivalents for labor and capital are typically derived from economy-wide ratios: approximately 253 MJ per work-hour and 16 MJ per monetary unit (with variations by economic system) [34][35].

1.5.8. Exergoenvironmental Analysis

Exergoenvironmental Analysis (AExA), coined by Meyer and Tsatsaronis, integrates thermoeconomic analysis with life cycle assessment to internalize external costs of pollutant emissions. This methodology extends traditional thermoeconomics by leveraging exergy as a comprehensive basis for both cost allocation and environmental impact evaluation within energy and material systems [36].

The AExA methodology proceeds through four key stages: (1) Exergy Analysis, conducting conventional exergy analysis to identify system irreversibilities and inefficiencies; (2) Life Cycle Assessment, performing LCA on the system and external inputs using validated impact assessment models; (3) Impact Allocation via Thermoeconomics, allocating LCA environmental impacts to system components and flows based on thermoeconomic principles to determine exergoenvironmental characteristics of each process stream; and (4) Comprehensive Evaluation, enabling combined assessment of thermodynamic performance and environmental impact [36].

The strength of integrating LCA into AExA lies in its system-wide scope and use of scientifically validated impact categories, thereby enhancing environmental relevance of the analysis.

1.5.9. Resource Exergy Analysis

Resource Exergy Analysis (REA) is an application-focused methodology for evaluating energy and material systems, particularly in district heating, cooling, and renewable energy integration. REA's distinctive contribution lies not in introducing energy quality—a universal principle underlying all exergy assessments—but in applying a specific resource criterion: exergy is valued only when representing storable, on-demand energy [37].

This criterion fundamentally shapes resource classification. Solar radiation and wind possess substantial exergy flux but are non-storable and non-dispatchable; therefore, the first storable secondary energy form (electricity or thermal energy) resulting from their capture designates the resource boundary. Geothermal energy, by contrast, qualifies as a true resource—it is continuously accessible, controllable, and on-demand. This distinction is critical when comparing renewable systems: photovoltaic electricity is the resource, whereas incident solar exergy is not.

REA incorporates both First and Second Laws of Thermodynamics, accounting for irreversibility and energy quality in system assessment. A key element is its treatment of co-production systems through the Carnot method, which distributes fuel exergy and emissions between outputs proportional to their exergy content. This exergy-based approach is scientifically rigorous because it reflects actual thermodynamic value of each output, eliminating arbitrary assumptions in conventional allocation methods. At the same time, it requires much less process data than exergy-based allocation that follows process flows.

REA proves particularly valuable for evaluating systems where conventional primary energy factors provide misleading results—especially heating and cooling technologies. When combined with emissions analysis, REA helps identifying climate-optimal technology combinations by quantifying both direct and indirect emissions associated with resource consumption and inefficiencies [37][38].

To enhance transparency and accessibility, Jentsch developed Exergy Passes visualization tools [39] that decompose exergy into the product of energy and energy quality, making REA results comprehensible to non-specialists. These diagrams illustrate resource flows from supply to demand, revealing where thermodynamic inefficiencies occur and quantifying the mismatch between supply quality and demand requirements.

1.6. Comparison of Exergy Methods

The ongoing development of exergy-based methodologies reflects a shift toward increasingly specialized resource accounting frameworks, driven by both conceptual refinement and practical operational needs. Later methods do not necessarily offer greater comprehensiveness; rather, they may prioritize objectives such as minimal data requirements, the avoidance of uncertain assumptions, or ease of application. This evolution has resulted in a diverse set of exergy-based tools—each tailored to address specific questions within a given data framework.

Understanding this methodological trajectory clarifies how differing focuses emerged and highlights the disciplinary advances underlying exergy integration into life cycle assessment.

Early Resource Scope Developments: Initial exergy applications focused narrowly on energetic resources. CExD [21] represented a pivotal advancement by integrating both energetic resources (fossil fuels, biomass, nuclear) and non-energetic materials (metals, minerals, water) into a unified thermodynamic framework operationalized within the ecoinvent database. This methodological expansion recognized that resource depletion encompassed far more than energy extraction, necessitating a comprehensive exergy accounting that could address material and energy flows simultaneously.

System Boundary Refinements: Subsequent methodological development focused on system scope. CEENE [29] extended CExD's technosphere boundaries by incorporating land use as an exergy flow, accounting for the natural productivity sacrificed by human occupation. This boundary expansion recognized that complete resource accounting must encompass the ecosphere's contribution to resource generation—reflecting evolved understanding that human resource consumption represents exergy extraction from natural systems, not merely from already-concentrated technological resources.

Integration of Economic and Social Dimensions: A complementary development trajectory incorporated non-physical production factors. Extended Exergy Accounting (EEA) [40] extended thermodynamic accounting to capital and labor inputs by converting these to exergy equivalents, enabling integrated environmental-economic-social sustainability assessment within a single metric. While this extension addresses the recognized incompleteness of purely physical resource accounting, it introduces methodological complexity and ongoing debate regarding the validity and universality of labor-to-exergy conversion factors.

Process-Oriented Refinement: Exergetic Life Cycle Assessment (ELCA) [22] and subsequently Exergoenvironmental Analysis (AExA) [36] refined exergy's application toward process-level optimization by quantifying irreversibilities and allocating environmental impacts to system components based on thermodynamic principles. This development shifted emphasis from aggregate resource depletion assessment toward identifying specific inefficiencies and improvement opportunities within energy systems.

Practical Application Specialization: Resource Exergy Analysis (REA) [37] represents a specialized methodological development prioritizing practical energy system evaluation. REA introduced a distinctive resource criterion—only storable, on-demand energy qualifies as a resource—reflecting recognition that thermodynamic potential alone is insufficient for resource valuation; controllability and human utility must also be considered. The Carnot method for co-production allocation exemplifies REA's contribution to rigorous allocation methodologies.

This methodological evolution demonstrates conceptual progression from simple energy accounting toward multidimensional sustainability assessment frameworks that increasingly recognize resource complexity, system boundaries extending into natural ecosystems, integration of non-physical production factors, process-level efficiency optimization, and practical applicability constraints. Each advancement addressed perceived limitations or incompleteness of preceding approaches, reflecting discipline maturation and enhanced understanding of sustainable resource management requirements. The next step, in the author's opinion, is to further increase the comprehensiveness and precision of methodologies while ensuring that all life cycle stages and relevant aspects are integrated, enabling frameworks that are both holistic and rigorous.

Table 1. Comparison of exergy methods

Method	***Scope***	***Limitations***
Cumulative exergy content	Quantifies cumulative exergy of natural resources (energy and materials) in production processes	Excludes ecological system exergy (land-use)
Thermo-Ecological Cost	Quantifies non-renewable primary exergy consumption including environmental penalties	Restricted to non-renewable resources; excludes renewable and ecological contributions
Cumulative Exergy Extraction from Natural Environment	Assesses eight resource categories including land use based on net primary productivity	Does not account for emission toxicity; NPP data dependent
Industrial/Ecological Cumulative Exergy Demand	ICExD: industrial exergy; ECExD: includes ecosystem exergy expended for resource generation	Sectoral aggregation limits process-level resolution; input-output data dependent
Emergy analysis	Quantifies products in solar energy equivalents using transformity factors	Transformity calculation methodology debated; difficulty with non-solar energy conversion
Exergy life cycle assessment	Quantifies full life cycle irreversibilities and thermodynamic inefficiencies across stages	Emissions treated as exergy losses without toxicity reflection; data-intensive
Extended exergy accounting	Integrates material, labor, and capital as unified exergy equivalents	Conversion factors region- and time-specific; validity of non-physical factor conversion debated
Exergoenvironmental analysis	Integrates thermoeconomics with LCA; allocates environmental burdens via exergy principles	Complex methodology; LCA data quality dependent; computationally intensive, focus on LCA categories, weighting problem remains
Resource Exergy Analysis	Focuses on storable resources, and usability with limited data, enables distinct separation of energy and energy quality to increase transparency	Complex, hard to model interactions are not considered such as capital, laber and land-use changes, Not suitable for optimization of systems using non-storable exergy as input (Solar, Wind, Waves)

1.7. Research Objectives and Questions

The central aim of this research "A Framework for Exergetic Life Cycle Assessment of Residential Buildings" responds to an ongoing gap between conventional LCA methodology and its practical effectiveness in fully capturing both overt and hidden environmental impacts associated with the construction sector. Integrating exergy analysis with life cycle assessment seeks to enable a more precise and comprehensive accounting of building-related resource consumption, emissions, and environmental impacts. While previous exergy-based LCA methods have demonstrated the feasibility of integrating exergy with LCA, their frameworks generally encompass all resource types, including both storable and fluctuating (non-storable) sources.

The distinguishing feature and innovative contribution of this study is its exclusive focus on storable resource exergy. By isolating storable resources, the method externalizes the conversion processes from fluctuating sources (such as solar or wind) to storable energy carriers, and thereby avoids the excessive impact commonly found when all resource exergy is included.

The main advantage of the storable exergy-based approach is its limited data requirements and its targeted resource treatment, offering a practical, robust indicator for environmental impact assessment in the built environment. The specific aim of this study is to implement exergy-based LCA at the whole-building scale, illustrating how storable exergy can serve as a holistic and actionable resource indicator. This enables systematic environmental evaluation of alternative energy systems, and supports improved decision-making for sustainable design and building operation.

The study addresses a core research question: Is it more sustainable, considering resource use and emissions from an exergy perspective, to renovate an existing residential building or to construct a new one using improved materials and low-emission heating systems? A representative German multi-family house is analyzed in three main scenarios: (1) the current (old) building; (2) a renovated building with upgraded systems and improved envelope; (3) demolition and new construction employing advanced heating, low-impact materials, and optimized components. While Figure 1 provides an expanded framework for longer-term scenario optimization, the scope of this thesis is focused on comparing these three scenarios under predefined assumptions for heating system choice, building materials, and primary building elements.

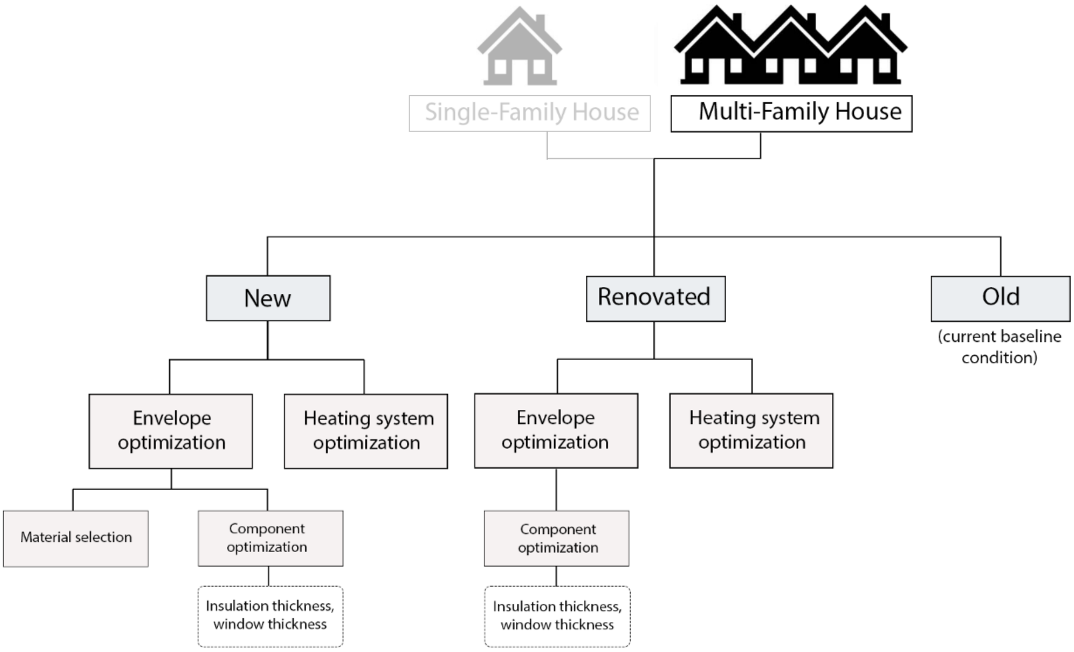


Figure 1. Scenarios under study (*own illustration)*

For the renovation scenario, the thesis evaluates an upgrade to heating system, enhancement of construction components, and improvement of thermal insulation. In the new-build case, attention is given to integrating updated heating system, optimized building components, and materials selected for minimized environmental impact.

The overarching goal is to determine which approach yields the lowest total life cycle environmental impact, measured as Overall Exergy Impact (OExI). The assessment concentrates on critical elements expected to exert the highest influence on exergetic performance, using exergy-based LCA to quantify energy use, emissions, and material resource flows in exergy terms. The research covers all life cycle stages from raw material extraction (A1) to end-of-life disposal (C4), adhering to standard building LCA conventions and facilitating consistent, transparent comparison of alternatives.

2. Methodology

2.1. Overview

The research methodology employed in this study consisted of a literature review of exergy theory and its integration into life cycle assessment (LCA), emphasizing applications within the built environment and building systems. This review enabled the identification and comparison of various exergy-based methodologies. Consequently, an approach was selected and further adapted to match the research objectives, with the evaluation process focusing on the scope, applicability, and limitations of each method.

Building upon this analysis, a tailored methodology was developed that combines physical and chemical resource exergy analysis with the LCA framework to diagnose thermodynamic inefficiencies in building systems. This hybrid approach supports decision-making regarding retrofitting of existing buildings and optimization in new constructions. The rationale for this method arises from the observation that previous exergy methods seldom distinguish between storable and non-storable resource exergy; as a result, they may overstate the importance of solar and wind exergy contributions—which, unlike storable resources, are not typically subject to depletion or storage-related inefficiencies in the same way. By focusing on resource exergy (chemical and physical, as relevant for thermal systems such as heat pumps, geothermal, or waste heat), this study's approach avoids these confounding factors and improves the accuracy of cross-system comparisons within the built environment. The method's limitations, underlying assumptions, and sources of uncertainty are discussed in Section 5 "Uncertainty and limitations", with validation performed in Section 4.2 "Validation of results".

Both physical exergy (especially from temperature-driven flows relevant to thermal heating systems) and chemical exergy (associated with the composition and concentration gradients of substances) are considered as part of the resource exergy analysis. This comprehensive treatment enables more accurate quantification of resource degradation and system irreversibility throughout the building life cycle. Importantly, solar, wind, and wave exergy inputs are excluded to avoid overemphasizing non-storable flows, since their optimization involves different criteria (e.g., cost, land use) and is not directly comparable to the use of fossil or storable renewable resources.

In this study, the exergy analysis of the building is conducted within a life cycle assessment (LCA) framework, with system boundaries defined as cradle-to-grave. This encompasses all life cycle stages, from material extraction and manufacturing, through the operational use phase, and ultimately to demolition and disposal. The analysis adopts a functional unit of 1 m^2 over a reference period of 50 years, reflecting standard practice for this building typology and supporting the applicability of results to real-world scenarios and cases.

2.2. Exergy-based LCA Framework

2.2.1. Exergy-Based Life Cycle Impact Categories

To account for the building's environmental impacts across its entire life cycle from an exergetic perspective, the exergy analysis is organized into three main categories. As depicted in Figure 2, these categories are designed to provide a holistic representation of life cycle exergy impacts, enabling evaluation not only of each impact category independently but also of the trade-offs and interdependencies among them.

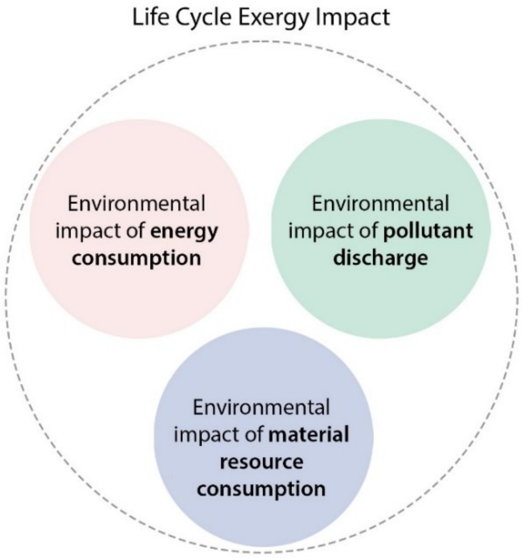


Figure 2. Life cycle Exergy Impact of different environmental impact categories under study (*own illustration)*

2.2.2. Treatment of Recurring and Non-Recurring Processes

During the development of the methodological framework, it was recognized that certain life cycle elements exhibit fundamentally different characteristics. The building's life cycle inventory can be classified into two primary categories. The first category comprises recurring processes that persist throughout the operational phase of the building's lifespan, such as the energy required for lighting, equipment operation, and other building services. Consequently, even if the building remains in operation beyond the defined LCA timeframe, the recurring operational impacts continue to accrue and are incorporated into impact calculations. In standard static LCA calculations, these processes are typically modeled using a fixed electricity grid mix and energy profile for the full reference period (here, 50 years), without annual updating for changes in the grid electricity origin. It is notable that the limitation of static LCA modeling could be problematic for electricity-intensive systems, as it may not reflect future energy supply transitions; however, since electricity comprises only a minor share of total energy demand in this study, the impact of future grid changes on results is negligible, and potential solutions such as dynamic grid modeling are reserved for future research.

The second category includes non-recurring processes, which occur only once or a limited number of times; such as material production or initial construction, and are characterized by impacts that are calculated for a single or limited occurrence and then distributed across the designated building lifetime. As a result, the environmental or exergetic burden associated with these processes is theoretically considered to be "paid off" once the defined reference period has elapsed. For subsequent analysis periods extending beyond the original scope, such impacts are not typically reapportioned unless additional interventions occur.

In order to address differences in lifespan between various building scenarios defined for this study and to ensure the methodological robustness of scenario comparison, this study accounts for recurring and non-recurring categories separately. This decision is also methodologically important because different calculation approaches are applied to each category. This separation clarifies the use of distinct methods, reflected in detailed explanations in section 2.3, and the interpretation of results, supporting robust scenario comparison. The implications of this approach for this study and the categorizations defined based on this distinction are visualized in Figure 3.

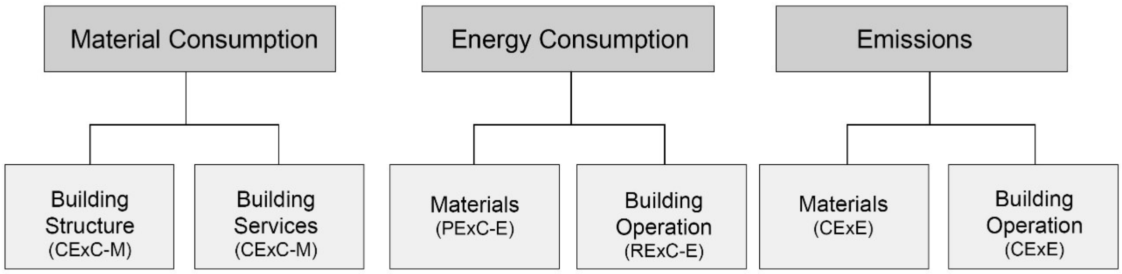


Figure 3. Calculation categories (*own illustration)*

In this image, material consumption for the building structure refers to the construction materials used for the physical parts of the building. Material consumption for building services represents the materials required for the manufacturing, installation and operation of heating supply systems. Both energy and emissions are divided into two subcategories. The 'materials' category includes energy use and emissions arising from manufacturing, processing, and all other life cycle stages up to disposal that relate to materials. The 'building operations' category covers energy use and emissions associated with the operation of the building, such as heating. The detailed description of each of the categories in Figure 3 and the process to calculate the exergy for these are presented in the section 2.3.

2.2.3. Proof of Concept Case Study

To test and demonstrate the applicability of the proposed exergy-based LCA framework, a case study was selected as a proof of concept. For this purpose, an analysis of German residential building typologies was conducted, and a representative building constructed in 1999 was chosen. This case, described in more detail in Section 3 "Case Study," reflects a prevalent typology, offering practical relevance and supporting the transferability of findings to broader building stock assessments.

The selected building predates contemporary energy efficiency standards but utilizes construction techniques and materials that remain widespread in the existing building stock. Its inclusion ensures the results are grounded in real-world practice and enhances the reliability of technical documentation used for modeling data and LCA inputs.

Figure 4 illustrates the temporal scope adopted for this study. The "Old" scenario reflects all original assumptions in terms of building structure and envelope and heating system. The study assumes three possible trajectories for the building after 25 years from its construction date: continued operation in its original state (Old scenario), refurbishment of building components and replacement of the heating system (Renovated scenario), or complete demolition and reconstruction with updated materials and systems (New scenario). To ensure comparability among scenarios, the analysis begins in 2025 and is projected over a 50-year time span, extending to 2075.

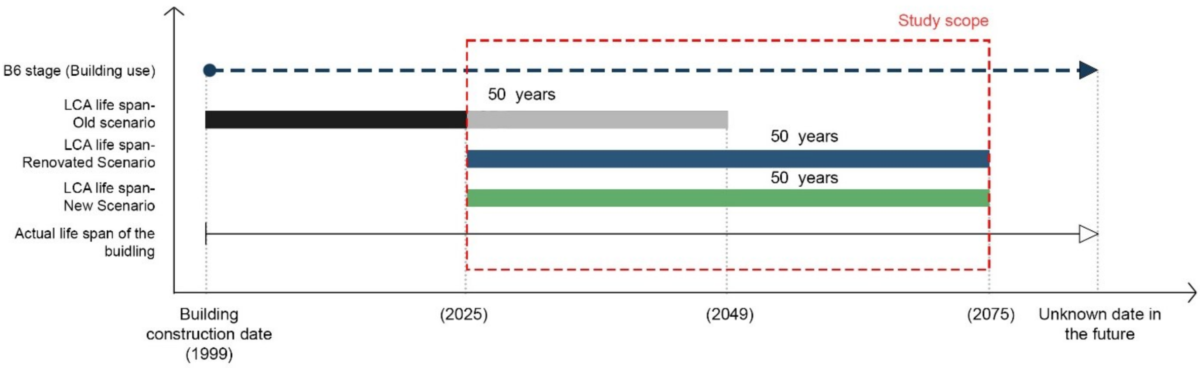


Figure 4. Time scope and assumptions of the study (*own illustration)*

In accordance with previously discussed distinctions between recurring and non-recurring process impacts, the non-recurring environmental burdens of the old scenario are considered to be fully distributed and accounted for by 2049. However, recurring energy and operational impacts continue for the entire lifetime of the building, even beyond 2049. This represents a theoretical scenario, as in reality, additional non-recurring burdens such as new windows or internal refurbishment might be expected even after 50 years. Evaluating the environmental and thermodynamic performance of renovation or reconstruction scenarios requires that any remaining, unfulfilled non-recurring impacts of the old scenario be appropriately allocated to the renovated and new scenarios. This approach is justified because the intervention (renovation or reconstruction) is assumed to occur in 2025, prior to the full amortization of the original environmental burden associated with non-recurring processes.

Figure 5 provides an overview of the methodological process from collecting inventory data through inventory analysis and culminating in the calculation of Overall Exergy Consumption (OExI).

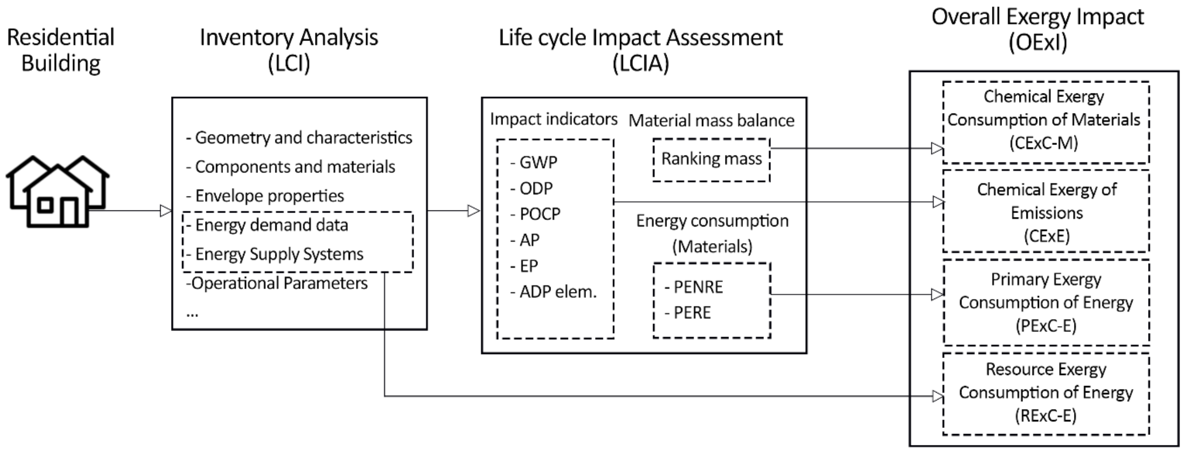


Figure 5. Methodology scheme and steps (*own illustration)*

Initially, an LCA is performed for all three scenarios to establish the relevant material and energy flows across the system boundary. Subsequently, a combination of detailed inventory data and LCA results forms the basis for calculating the OExI associated with each scenario. This sequential approach ensures that thermodynamic irreversibilities, resource quality degradation, as well as resource scarcity (for materials) are systematically quantified throughout the building's life cycle, facilitating an integrated exergy-based performance assessment.

2.3. Calculation Approach

2.3.1. Life Cycle Assessment

To quantify environmental impacts for each scenario, this study employed the eLCA software [43]. eLCA is a browser-based tool developed by the German Federal Institute for Research on Building, Urban Affairs, and Spatial Development (BBSR) for generating life cycle assessments (Ökobilanzen) of buildings. The platform integrates the ÖKOBAUDAT database [58], Germany's national repository for environmental product declarations (EPDs), allowing material specifications within digital building models to be directly linked to current environmental data. eLCA also enables data import from energy compliance software (e.g., EnEV or DIN 18599-based tools), streamlining the workflow[42].

The analysis in this study was conducted using eLCA version 0.9.7 [43]. The methodology underlying the assessment follows the principles set forth in Germany's Sustainable Building Assessment System (Bewertungssystem Nachhaltiges Bauen, BNB) and the European standard EN 15978 [59], which defines the life cycle environmental calculation of buildings. ÖKOBAUDAT version 2023_I_A1, compliant with EN 15804+A1, provided the inventory data. The ÖKOBAUDAT database itself is underpinned by the GaBi background data, ensuring traceability and consistency in LCA data quality.

The eLCA tool is classified as a component catalogue software [44], utilizing tabular entry of material and component quantities which are then multiplied by embedded environmental data to compute total impacts throughout a building's life cycle. In this workflow, operational energy demand must be calculated separately and subsequently entered into eLCA, as operational performance is not automatically linked to building envelope parameters. For this reason, energy demand calculations in this study were performed outside of eLCA and integrated into the tool's analysis as separately modeled inputs.

2.3.2. Data Inputs

Material Input

For the inventory analysis phase of the life cycle assessment, a comprehensive table of all material inputs, components, and layer configurations is required. Modeling tools—both BIM and non-BIM platforms—can be used to accurately quantify material usage across building elements. For this study, AutoCAD software was employed to model the building and extract quantitative data for each component.

Energy Demand Input

The energy demand of a building encompasses all energy required for proper operation, including heating, cooling, ventilation, air conditioning, lighting, appliances, and equipment. In a fully detailed calculation, this process begins with a definition of building geometry, usage type, and boundary conditions such as envelope properties, floor area, orientation, thermal zones, and occupancy schedules. With these inputs, the primary energy demand can be determined, either manually or using specialized software.

However, in this study, a simplified method was employed to estimate operational energy and exergy consumption, reflecting a generic building type rather than a specific case. Instead of conducting detailed modeling, published reference values for residential buildings were utilized—specifically, the Exergy Pass demand table and data from the Fraunhofer Institute [49]. This approach enables consistent, scenario-based comparisons while avoiding the high data requirements associated with detailed modeling for each individual building. The necessary operational energy inputs were determined externally and then entered into the eLCA software to support the life cycle resource use calculations. This method focuses on illustrating the comparative performance of building systems under standardized conditions, rather than generating custom results for a specific property.

2.3.3. Exergy of Energy Consumption

Method 1: In this study, exergy calculation for Resource Exergy Consumption of Energy (RExC-E) is performed using the Resource Exergy Analysis (REA) method, as detailed in the REA calculation guide and documented by Jentsch and the AGFW [37, 38]. The REA approach stands apart from conventional cumulative exergy demand (CExD) or energy LCA indicators by providing a physically rigorous quantification of resource exergy consumption, explicitly distinguishing between storable (on-demand) and non-storable (transient, non-dispatchable) energy forms. Exergy analysis for the use phase is conducted with the Exergy Pass tool [39], which operationalizes REA principles to determine building- and system-level exergy flows.

The REA method was selected over conventional exergy or energy-based approaches due to its better suitability for the research question: What is the more environmentally friendly system. Unlike other methodologies, REA clearly separates storable and non-storable resources, preventing excessive impact of fluctuating renewable energy contributions, that is lost unless used and ensuring a more balanced comparison between energy technologies. This distinction is essential for the sensible assessment of modern building energy systems, which increasingly integrate fluctuating renewables and combined technology solutions. Results are validated against the Cumulative Exergy Demand (CExD) methodology in the Validation section (Section 4.2), enabling comparison of LCA-derived Primary Exergy Consumption of Energy (PExC-E) with REA-based calculations.

Method 2: The exergy assessment of energies associated with material production across all LCA stages—from material extraction (A1) through disposal (C4)—is performed by converting primary energy data to exergy equivalents using quality factors. This approach translates the thermodynamic content of energy carriers into an exergy basis.

The Primary Exergy Consumption of material-related energies (PExC-E) for a specific fuel type is calculated as:

$$PExC\text{-}E = PEC_i * \beta_i * p_i \qquad (1)$$

where PEC_i represents the primary energy consumption for fuel type i, β_i is the exergy-to-energy ratio (quality factor), and p_i is the fractional share of fuel i.

PEC values are extracted from the eLCA online tool, reported as Primary Renewable Energy (PERE) and Primary Non-Renewable Energy (PENRE). These indicators quantify total primary energy extracted from nature across all life cycle stages, including upstream and downstream energy consumption.

Since the Exergy Pass tool using the REA method only allows calculations for energy supply systems—and here, the specific systems providing energy for material-related processes could not be identified in the LCA tool—the PExC-E method was employed for this category. Because of this, a significant uncertainty arises from the methodological distinction between this LCA-based approach (Method 2) and the REA method used for operational energy

(Method 1). Notably, Method 1 differentiates between storable and non-storable resources, while Method 2 does not.

Additionally, LCA databases do not specify energy source composition for individual material processes.

To address this limitation, the following assumptions are adopted:

PERE: $\beta = 1.0$ (assumed quality factor for renewable energy)

PENRE: $\beta = 1.04$ (natural gas proxy for non-renewable sources)

These assumptions are made for the purpose of methodological comparability and to avoid underestimating the theoretical exergy values of renewable and non renewable energy inputs when their conversion losses are unknown. These factors enable consistent exergy quantification but introduce uncertainty due to heterogeneous fuel mixes in actual industrial material production. This assumption is discussed further in the Limitations section.

It is also notable that from this point onward, the use of PExC-E as a term specifically refers to the primary Exergy consumption of Energy for materials unless otherwise stated.

2.3.4. Exergy of Material Consumption

Chemical Exergy Consumption of Materials (CExC-M) quantifies the exergy-based depletion of resources associated with construction materials in the building's life cycle. CExC-M is determined from the total material mass (MM) used in the building, as calculated in the LCA scenario—including initial inputs, replacement cycles, maintenance, and end-of-life flows, based on the reference service lives of building components. The material mass is taken from the life cycle evaluation phase in the eLCA software's mass balance and ranking mass outputs, reflecting all materials present in the modeled building system over its assessed lifetime.

To calculate CExC-M, each material's total mass is multiplied by its standard chemical exergy (SCExM), which represents the thermodynamic scarcity of the resource. The aggregation of exergy by material, rather than by simple mass, allows resource criticality to be included in the depletion metric—since exergy values rise for substances that are less abundant in the environment, highlighting the true depletion cost.

This calculation captures resource exergy depletion for the materials physically present in the building system (as defined by quantity take-off and LCA scenario) as well as upstream exergy losses that include all material exergy used but rejected before the final product (e.g., water, acids, and by-products lost during production and processing phases).

The calculation formula for CExC-M is:

$$CExC\text{-}M = MM * SCExM \quad (2)$$

where MM is the total material mass (kg), and SCExM is the Standard Chemical Exergy of the Material (MJ/kg). It is important to mention that the results presented in the results section are calculated by multiplying the amounts from this step by a reference conversion factor, aligning all exergy values to the functional unit of 1 m² over 1 year (per m²·a).

A detailed calculation process to obtain the standard chemical exergy value for each material (SCExM) involves summing the standard chemical exergy contributions of all constituent substance using the following equation:

$$SCExM = \sum_{i=1}^{n} \frac{(SCEx\ in\ kJ/mol)_i}{(molar\ mass\ in\ g/mol)_i} \quad (3)$$

Where SCExM is the standard chemical exergy for a material (MJ/kg), SCEx is the standard chemical exergy (kJ/mol) of constituent substance i, and is divided by the molar mass (g/mol) of substance i. Standard chemical exergy values for pure substances can be found in the literature, such as Szargut's [46]. However, determining the SCExM for complex building materials is substantially demanding, since many materials are composed of multiple constituents with varying exergy values, and detailed compositional data for commercial or proprietary products are frequently unavailable in public sources.

To address these challenges, this study employs a simplified approach, making use of pre-calculated SCExM values for common building materials from published sources— [45], which provide exergy values in MJ/kg. While this method offers transparency and practicality, it relies on reference values instead of full custom calculations. As a result, some limitations arise, particularly when certain materials in this study do not have directly corresponding exergy values in the reference source. This limitation is especially relevant for mineral wool insulation, which is used in all three scenarios and constitutes a major material difference between the old and renovated scenarios. The full list of materials and their associated exergy values is provided in the Appendix, with further discussion of this limitation in the "Limitations" section.

It is important to note that combining CExC-M and the PExC-E as defined in section 2.3.3, yields the total cumulative exergy for materials. but reporting them separately is necessary due to differences in calculation methods and data sources. Therefore, their values are kept independent throughout the report for methodological clarity and to ensure comparability and transparency in the assessment results.

2.3.5. Exergy of Emission Discharge

The exergy associated with life cycle emissions, mentioned as Chemical Exergy of Emissions (CExE) in this study, extends the CExD framework by quantifying dissipative exergy losses resulting from the release of environmentally relevant substances across the building's life cycle. Unlike resource exergy which measure input-based thermodynamic depletion, CExE quantifies the thermodynamic disequilibrium of emissions as environmental outputs. This approach is conceptually related to Cornelissen's Zero-ELCA methodology [22][33], which accounts for environmental problems by quantifying the exergy associated with emissions. However, this study employs a simplified direct exergy calculation approach rather than Cornelissen's more complex abatement exergy method. While Zero-ELCA calculates the exergy required to hypothetically remediate or neutralize emissions, the present approach calculates the inherent chemical exergy of emissions as discharged into the environment. This direct method is more straightforward and data-accessible, allowing systematic integration of emission impacts within exergy-based building assessment.

The CExE for each environmental impact category is calculated as the product of the emission mass equivalence (EM, in kg-eq) and the standard chemical exergy of the emission (SCExE, in MJ/kg):

$$CExE_i = EM_i * SCExE_i \qquad (5)$$

The SCExE for each emission is derived by dividing the standard chemical exergy of the substance (in kJ/mol) by its molar mass (in g/mol), yielding a value in MJ/kg:

$$SCExE_{i=1} = \frac{(SCExE\ in \frac{kJ}{mol})_i}{(molar\ mass\ in \frac{g}{mol})_i} \qquad (6)$$

Each LCA impact category is represented by a reference substance with a defined standard chemical exergy. Impact categories and their representative substances which are addressed in this study include:

Global Warming Potential (GWP): Carbon dioxide (CO_2), calculated in kg-CO_2-eq
Acidification Potential (AP): Sulfur dioxide (SO_2), calculated in kg-SO_2-eq
Ozone Depletion Potential (ODP): Chlorofluorocarbon-11 (CFC-11), calculated in kg-R-11-eq
Eutrophication Potential (EP): Phosphate (PO_4^{3-}), calculated in kg-PO4-eq
Photochemical Ozone Creation Potential (POCP): Ethene (C_2H_4), calculated in kg-C_2H_4-eq
Abiotic Depletion Potential - Elements (ADP elem.): Antimony (Sb), calculated in kg-Sb-eq [43]

The emission mass equivalence from LCA results is multiplied by the standard chemical exergy of the representative substance, enabling systematic conversion of environmental impact categories to exergy terms. The limitation of this method for calculating CExE is that the downstream effects are neglected. Downstream effects of emissions are the secondary environmental impacts that occur after pollutants are released, such as atmospheric chemical transformations forming acid rain, pollutant transfer between air-soil-water systems, and ecosystem disruptions like eutrophication and bioaccumulation.

This methodology ensures that both the quantity and thermodynamic quality of environmental emissions are systematically captured within exergy-based impact assessment. By accounting for the chemical exergy of pollutants, reflecting their capacity to alter environmental systems, CExE provides a more rigorous evaluation of irreversible environmental degradation compared to conventional mass-based impact metrics. The integration of CExE with RExC-E, PExC-E and CExC-M enables assessment of Overall Exergy Impact (OExI) across resource consumption and environmental emission perspectives.

2.3.6. Standard Chemical Exergy Values and quality factors

Standard chemical exergy values for substances and materials utilized in this study were compiled from several authoritative sources. The foundational dataset for standard chemical exergy of pure substances was derived from Szargut's reference text [46] (appendix- table 17). For compounds comprising multiple elements, such as CFC 11, and for certain building materials, values from Nwodo's recent study, based on the cumulative exergy demand (CExD) approach, were incorporated (appendix- table 16). Quality factors of fuels were also referenced from Szargut's dataset [45][46] (table 14).

For comprehensive data coverage in future studies, the utilization of life cycle inventory (LCI) databases, most notably Ecoinvent, is recommended. Ecoinvent provides extensive datasets on material, energy, and emission flows, which can be further analyzed (for example, by applying the Cumulative Exergy Demand method) to determine chemical exergy values of construction materials, fuels, and emission streams. However, due to licensing constraints, the present research was conducted using publicly available datasets, including published exergy values and results partially derived from Ecoinvent-based calculations where possible.

2.3.7. Methodological Limitations

There were some simplifications as well as some inconsistencies between different methods proposed and carried out in this study that can be sources of limitation, as explained in the following sections.

Energy Demand Calculation

The quantification of building energy demand relies on detailed building-specific information and computationally intensive calculations. To facilitate this proof-of-concept study while maintaining focus on building typology analysis, standardized simplified values from the Fraunhofer Institute were employed rather than performing individualized detailed energy calculations for each case. Consequently, the results may not fully represent the specific thermal and operational characteristics of individual buildings. Future studies requiring higher precision should implement detailed, building-specific energy simulations to capture variations in geometry, thermal properties, occupation patterns, and climate-specific factors.

Although scenario-based envelope improvements are implemented as detailed in section 3.2 “Explanation of scenarios”, the predetermined energy demand inputs based on standardized typological values do not dynamically adjust to reflect these modifications, resulting in a decoupling between actual building component interventions and modeled energy performance outcomes. This can limit the quantitative representation of retrofit effectiveness within this proof-of-concept assessment.

Life Cycle Inventory and Impact Assessment Uncertainties

The integrated LCA-exergy approach inherits inherent uncertainties from both methodological frameworks. The Life Cycle Impact Assessment (LCIA) calculations in eLCA software follow EN 15804 standardization, which defines impact category formation, characterization factors, and emission indicator methodologies. Research demonstrates significant variations in results across different LCIA methodologies, and the selection of EN 15804 consequently influences all downstream exergy calculations. Furthermore, the characterization factors and assumptions underlying PERE (Primary Renewable Energy) and PENRE (Primary Non-Renewable Energy) calculations are methodology-dependent and introduce subjective elements into the analysis.

Quantification of the Exergy of Emission

A significant limitation arises from eLCA software's aggregation of individual emissions into impact category equivalents. For example, Global Warming Potential (GWP) results are reported in CO_2 equivalents, obscuring the specific emission composition and proportions. Consequently, standard chemical exergy values were multiplied by equivalency factors rather than by the actual substance exergies. More rigorous analysis would require substance-level emission data prior to characterization, enabling precise exergy calculations for individual emissions before aggregation into impact categories.

A significant limitation in the calculation of CExE is the exclusion of downstream effects and processes, as the proposed method is based solely on chemical exergy calculation. This results in an incomplete picture, since downstream losses—such as exergy destruction during product use, recycling inefficiencies, and end-of-life treatment—are not captured. For a more comprehensive and thermodynamically consistent result, downstream processes and their associated exergy losses must be included in the future analysis.

Material Chemical Exergy Values

Chemical exergy values for building materials were sourced from literature rather than calculated from first principles due to computational complexity and data constraints. Comprehensive material exergy calculations typically require detailed inventory data on constituent substances and production processes, optimally accessed through specialized databases (e.g., GaBi, ecoinvent). Limited access to commercial platforms necessitated the use of pre-calculated literature values. Chemical exergy values were unavailable for several materials used across the three scenarios. This limitation was particularly significant for insulation materials, as they constitute one of the key differentiating factors between the old and renovated scenarios. This data gap introduces a notable limitation in capturing the full exergy accounting in terms of CExC-M. For comprehensive future research, all material chemical exergies should be calculated substance-by-substance, ensuring complete coverage of upstream and life cycle processes.

It should also be noted that although the CExC-M of building services associated with the materials used in the construction of heating systems is acknowledged within the methodological framework, this contribution is excluded from the calculations due to insufficient data availability.

Exergy Calculations Associated with the Energy Consumption

Two distinct methodological approaches were employed for the quantification of exergy associated with the consumption of energy: the RExC-E method for operational energy and the LCA-based conversion method PExC-E for energy consumption of materials. The latter approach, employing PERE and PENRE data multiplied by exergy-to-energy ratios (β factors), carries inherent uncertainty due to undefined energy source specifications in LCA databases. A default β factor of 1.0 was assigned to PERE (renewable energy) and 1.04 to PENRE (non-renewable energy proxy), reflecting assumed average quality factors. However, actual energy source composition varies considerably among industrial material production processes. Precise exergy quantification would require transparent documentation of specific energy sources, their proportions, and corresponding quality factors for each material production pathway. This methodological inconsistency between Methods 1 and 2—particularly regarding differentiation between storable and non-storable resources—represents a significant source of uncertainty when comparing material-related and operational energy exergies and should be addressed in future refinements of this framework.

3. Case Study

3.1. Introduction

The selected case study for this research is a two-story, back-to-back row house (Figure 6) with an east–west orientation, representative of the older multi-family residential building typologies commonly found in Germany. The building, part of the Ringstraße development project in Neu-Ulm, was designed by Fink + Jocher architects and completed in 1999 (Figures 7-10) . The structure consists of modular groups, each comprising three distinct dwelling units: two duplex apartments positioned back-to-back with one single-story apartment. The single-story unit is oriented to one side, while the duplex units feature a double-sided orientation and a roof terrace on the upper floor [47][48].

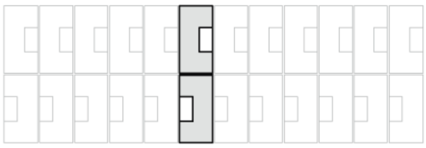


Figure 6. Case study building typology

Figure 7. Figures of the Project [47]

Figure 8. Ground floor plan [48]

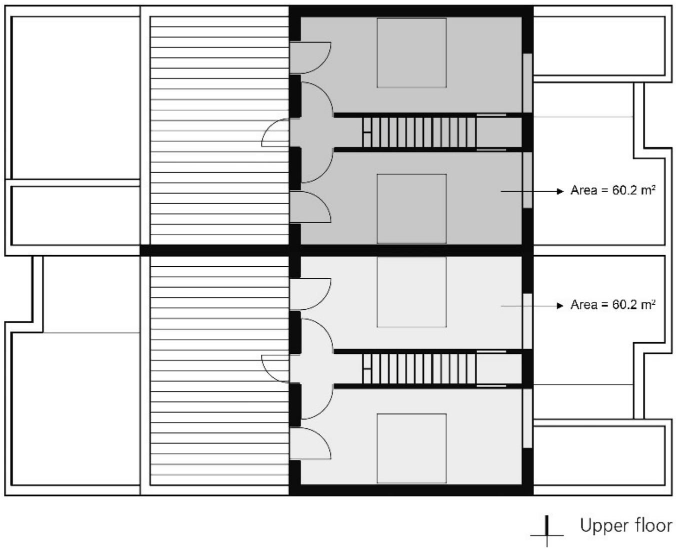


Figure 9. 1st floor plan [48]

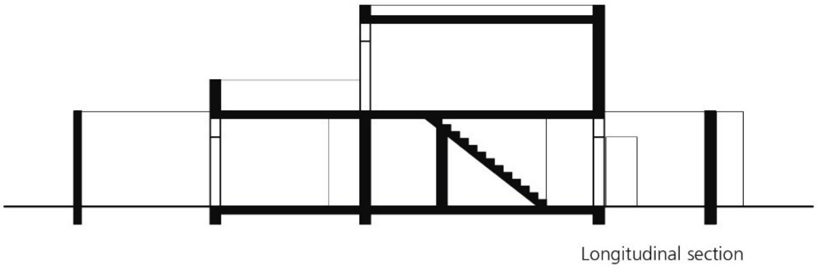


Figure 10. Building section [48]

The architectural design emphasizes spatial efficiency, characterized by compact floor plans with minimal circulation areas. In the single-story unit, private rooms are arranged around a central living space, whereas in the duplex apartments they are accessed via the staircase landing. Bathrooms are placed in a central zone running along the length of the building and therefore lack natural daylight access. Although the internal layout within each module is fixed, the overall urban configuration allows for structural adaptation, enabling the creation of high-quality outdoor spaces despite the compact building density [47][48]. The combined gross floor area of the three units amounts to 344.88 m², with a total net usable floor area of 254.09 m².

This building typology was deliberately selected as the case study base for three primary methodological reasons. First, the back-to-back row house represents a prevalent residential building typology in Germany, particularly in post-1990s urban developments. Analyzing a common, recognizable building type enhances the practical relevance and transferability of research findings to broader building stock assessment and policy applications. Second, the 1999 construction date positions this building at a methodologically advantageous juncture: it predates contemporary energy efficiency standards (such as Kreditanstalt für Wiederaufbau

(KfW) standards or Passive house criteria) yet employs construction techniques and materials that remain prevalent in standing stock. This temporal positioning makes the building representative of the "typical existing building" condition that retrofit interventions commonly address. Third, the building's modular unit structure, comprising three distinct dwelling types (single-story and duplex configurations) within a single module, provides architectural complexity relevant to real-world renovation decision-making. The presence of multiple unit types within one structure allows investigation of differentiated retrofit strategies and material choices, reflecting heterogeneous building compositions encountered in practice. Additionally, the relatively recent construction year (1999) and established track record enable access to reliable technical documentation, performance data, and material specifications.

3.2. Explanation of Scenarios

The following section outlines the main characteristics of each scenario. After the individual descriptions, a comparative summary of the three scenarios is presented in tabular form (Tables 3-5).

Old Scenario:

The old scenario represents the case study building in its original state. The building, constructed in 1999 in Neu-Ulm as part of a row house development, primarily employs reinforced concrete as its structural material. Additional details regarding the building structure and envelope, including walls, floors, ceilings, and other components, are derived partly from publicly available project information and partly from assumptions consistent with typical construction practices of that period and region. The details of building components and layering are presented in table 3.

The building's energy demand is estimated based on reference data for energy demand characteristics of residential row houses in kilowatt-hours per square meter per year (kWh/m²·a) provided by the Fraunhofer IBP: District ECA Analysis [49]. Since the building was constructed in 1999, the reference values used correspond to the period 1995–2006, which align with the German Energy Saving Ordinance (EnEV) 2002/2004.

Building service systems
Heating System

In the old scenario, a low-temperature gas boiler with a nominal output range of 20–120 kW is selected, consistent with the technological context and typical solutions available at the time of construction in accordance with the EnEV requirements. System specifications and performance data for the use in eLCA software are derived from the ÖKOBAUDAT database.

The seasonal efficiency of the boiler is specified as 91.4% at a partial load of 30%, with an average operational efficiency maintained at 91.4% [50].

For the calculation of RExC-E in Exergy Pass software, natural gas (without higher heating value utilization), fired with gas or oil, was selected. The annual net efficiency of a conventional gas boiler was defined as 0.83 (based on the lower heating value of the fuel used). This dual selection of heating systems in different software introduces uncertainties, as each software uses distinct assumptions and parameters. To minimize such uncertainties in future analyses, it is advisable to apply consistent software and methodological choices throughout the calculations.

Lighting and equipments

The lighting system comprises a combination of energy-saving lamps and traditional incandescent lamps, reflecting standard practice during the reference period. The selection of equipment follows the requirements of Standard 2012 [49], which characterizes the energy performance benchmarks of electrical devices used in this scenario.

Renovated Scenario:

The renovated scenario assumes that the existing building structure is preserved while key building components are upgraded to meet current energy efficiency regulations and standards. These improvements result in an enhanced thermal envelope with reduced heat transfer between the internal and external environments, leading to a lower overall energy demand. Additionally, the outdated heating system is replaced with a modern, more sustainable system that provides heat with a significantly reduced carbon footprint.

To ensure compliance with updated regulatory frameworks associated with improved envelope performance, this scenario applies reference values corresponding to the years 2007–2012, consistent with the EnEV 2007/2009. The primary modifications in this scenario, compared to the old version, involve two categories: building components and the heating system. An overview of the building component specifications for the Renovated scenario is provided in Table 4.

Renovated Building Components
External Walls

In the existing scenario, the external walls consist of reinforced concrete with a 60 mm mineral wool insulation layer, resulting in a typical thermal transmittance (U-value) of approximately 0.45–0.50 W/m²K. To meet the target values specified by the Energy Saving Ordinance (EnEV 2007), which requires U ≤ 0.28 W/m²K, an additional external insulation layer is introduced in the renovation scenario. The new configuration includes an extra 120 mm of mineral wool insulation, leading to a total insulation thickness of 180 mm. Assuming a thermal conductivity (λ) of approximately 0.04 W/mK, the resulting U-value is expected to range between 0.25 and 0.28 W/m²K.

Roof

The existing roof structure consists of a reinforced concrete slab with an external insulation layer. In the old scenario, a 100 mm layer of mineral wool insulation typical for flat roofs is applied, corresponding to a U-value of approximately 0.30–0.35 W/m²K. To meet the requirements of EnEV 2007, which stipulates U ≤ 0.20 W/m²K (with preferred values around 0.15–0.18 W/m²K), the renovation scenario considers adding an additional 100 mm layer of mineral wool insulation on the interior side of the roof. This approach minimizes structural modifications while achieving a total insulation thickness of 200 mm. The improved configuration is expected to yield a U-value in the range of 0.16–0.18 W/m²K.

Ground Floor

In this project, the ground floor is constructed directly above a reinforced concrete slab foundation. In the old scenario, the assembly includes a 40 mm insulation layer with an estimated U-value of 0.45–0.50 W/m²K. To comply with the EnEV 2007 target requirement of U ≤ 0.30 W/m²K, the renovated scenario introduces an additional 100 mm mineral wool insulation layer placed above the existing structure. This results in an overall U-value of approximately 0.25 W/m²K.

Windows and Glazing

For the old scenario, double-glazed windows typical of the late 1990s are assumed, with a U-value of approximately 2.8–3.0 W/m²K. The renovation scenario targets a significantly improved performance with a U-value (Uw) of no more than 1.3 W/m²K. To achieve this, the existing glazing is replaced with low-emissivity (low-E), argon-filled triple glazing, featuring a glass U-value (Ug) of 0.6–0.7 W/m²K. The window frames are replaced with models incorporating improved thermal breaks and airtight gaskets, resulting in an estimated overall window U-value (Uw) of 1.0–1.1 W/m²K. Although enhanced airtightness measures, such as tape sealing of window junctions, are recommended, they are not explicitly included in the modeling due to practical limitations.

Building service systems
Heating System

In the renovated scenario, the original gas boiler is replaced with a pellet boiler system rated at less than 20 kW, consistent with the requirements of the EnEV, and classified as a renewable energy source. The selection and specification of this system are based on data provided in the ÖKOBAUDAT database and is used for modeling in eLCA software. The operational efficiency of the pellet boiler is defined as 87%, assuming the presence of a buffer storage system to optimize performance [51].

For the calculation of RExC-E using the Exergy Pass tool, a modern wood-fired boiler—operating without utilization of the higher heating value and fired with wood chips or pellets—was selected. The annual net efficiency of this boiler is defined as 0.8, based on the lower heating value of the fuel used. This parameter represents the average operational efficiency for a contemporary biomass boiler under typical annual conditions.

Lighting and equipments

Lighting systems in the renovated scenario comprise a combination of light-emitting diode (LED) fixtures, fluorescent tubes, and energy-saving lamps [49], contributing to reduced electricity demand compared to conventional lighting solutions. For electrical equipment, it is assumed that all selected appliances adhere to Efficiency Class A, further minimizing total energy consumption.

New Scenario:

In the new scenario, it is assumed that the existing building is demolished and replaced with a newly constructed building. The new structure employs a heating system identical to that specified in the renovated scenario. The building components, including exterior and interior walls, ceiling, and roof, are redesigned with new construction details, with timber adopted as the main structural material in place of reinforced concrete as used in the old scenario. A comprehensive overview of the building component specifications for the new scenario is provided in Table 5.

Building service systems
Heating System

For the new scenario, the same pellet boiler system as adopted in the renovated scenario is implemented. The specification and selection of the system for use is eLCA software are based on data from the ÖKOBAUDAT database. [46] and for the use in Exergy pass software following specification for the boiler without higher heating value utilization with specifications similar to which introduced for renovated scenario.

Lighting and equipments

Lighting systems in the new scenario incorporate a mix of light-emitting diode (LED) fixtures, fluorescent tubes, and energy-saving lamps, consistent with the approach taken in the renovated scenario. All electrical equipment is assumed to meet Efficiency Class A standards, aligning with the energy efficiency measures applied in the renovated scenario [49].

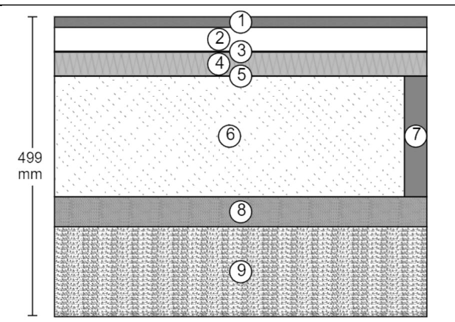
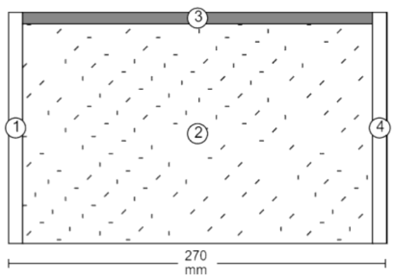
Table 2.Summary of scenarios

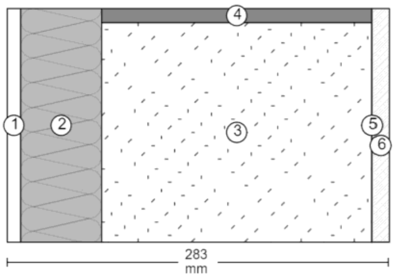
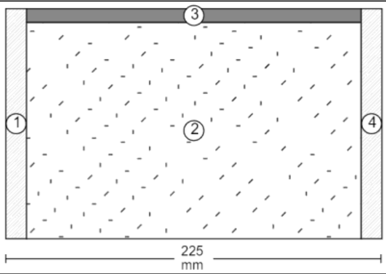
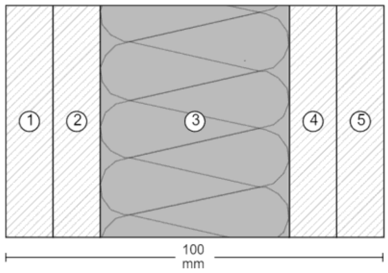
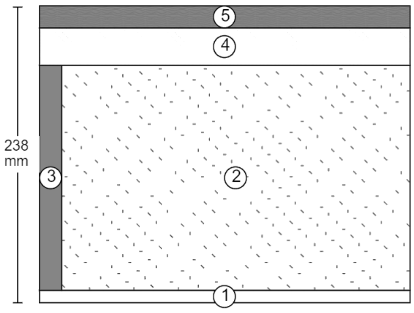
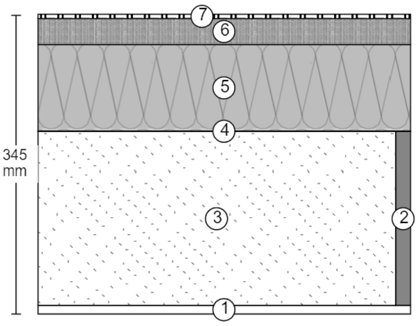
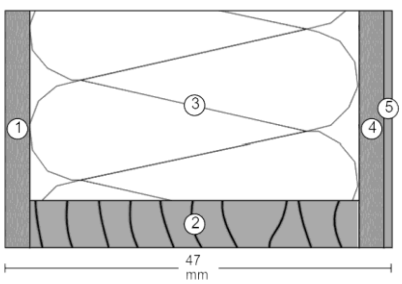
Characteristics	Old	Renovated	New
Main structural material	Reinforced Concrete	Reinforced concrete	Timber
Heating system	Fossil boiler (Conventional low-temperature)	Renewable boiler (Wood pellets)	Renewable boiler (Wood pellets)
Ventilation type	Window ventilation	Window ventilation	Window ventilation
Equipment type	Standard 2012	Efficiency class A	Efficiency class A
Lighting type	Mix energy saving lamps / incandescent lamp	LED / fluorescent tubes / energy saving lamps	LED / fluorescent tubes / energy saving lamps
Deductions*	Medium	Efficient	Efficient
Heating demand kWh/m^2.a	115	72	72
Hot water demand kWh/m^2.a	34	34	34
Energy for lighting kWh/m^2.a	12	4	4
Energy for equipment kWh/m^2.a	18	14	14

*Deductions: simplified deductions from the energy requirements for heating by waste heat from household appliances and lighting. Efficient refers to LEDs + Efficiency class A equipment, Old refers to Incandescent lamps + standard equipment, Medium refers to mean value from Efficient and Old [49]

3.3. Building Component Details

Table 3. Old Building Scenario components

Flooring + foundation (Ground floor)		1. Solid wood parquet (German average), 17.60mm 2. Cement screed, 40.00mm 3. PE foil, dimpled, 1.25mm 4. Mineral wool (floor insulation), 40.00mm 5. Damp insulation PA, 0.20mm 6. Ready-mix concrete C20/25, 200.00mm 7. Reinforcement steel wire, 200.00mm 8. Sand 0/2, 50.00mm 9. Gravel (Grain size 2/32), 150.00mm
Exterior non load-bearing wall		1. Rendering mortar – Reinforcement Fibre Plaster, 10.00mm 2. Ready-mix concrete C20/25, 250.00mm 3. Reinforcement steel wire, 250.00mm 4. Rendering mortar – Reinforcement Fibre Plaster, 10.00mm

Exterior load-bearing wall		1. Mineral pre-made mortar: rendering mortar – Reinforcement Fibre Plaster, 10.00mm 2. Mineral wool (facade insulation), 60.00mm 3. Ready-mix concrete C20/25, 200.00mm 4. Reinforcement steel wire, 200.00mm 5. Damp insulation PA, 0.10mm 6. Gypsum plaster board (fire protection) (12.5 mm), 12.50mm
Load-bearing interior walls		1. Gypsum plaster board (fire protection) (12.5 mm), 12.50mm 2. Ready-mix concrete C20/25, 200.00mm 3. Reinforcement steel wire, 200.00mm 4. Gypsum plaster board (fire protection) (12.5 mm), 12.50mm
Non load-bearing interior walls		1. Gypsum plaster board (perforated board) (12.5 mm), 12.50mm 2. Gypsum plaster board (impregnated, moisture resistant) (12.5 mm), 12.50mm 3. Mineral wool (partition walls insulation), 50.00mm 4. Gypsum plaster board (impregnated, moisture resistant) (12.5 mm), 12.50mm 5. Gypsum plaster board (fire protection) (12.5 mm), 12.50mm
Ceiling Structure		1. Mineral pre-made mortar: rendering and plastering mortar – normal/finishing render or plaster, 10.00mm 2. Ready-mix concrete C20/25, 180.00mm 3. Reinforcement steel wire, 180.00mm 4. Cement screed, 30.00mm 5. Solid wood parquet (German average), 17.60mm
Roof Structure		1. Mineral pre-made mortar: rendering and plastering mortar – normal/finishing render or plaster, 10.00mm 2. Reinforcement steel wire, 200.00mm 3. Ready-mix concrete C20/25, 200.00mm 4. Bitumen sheets G 200 S4, 0.20mm 5. Mineral wool (flat roof insulation), 100.00mm 6. Gravel (Grain size 2/32), 30.00mm 7. EPDM roof sheets, 5.00mm
Exterior Doors		1. Laminated veneer board, 3.00mm 2. Glued laminated timber - straight shapes (German average), 40.00mm 3. Mineral wool (partition walls insulation), 40.00mm 4. Laminated veneer board, 3.00mm 5. Steel sheet (0.3-30mm), 1.00mm Additional: -frame profiles for doors - Verband Fenster + Fassade - frame profile for fire control doors made of (stainless) steel, 6 m -Joint sealing strips, butyl, 8 m

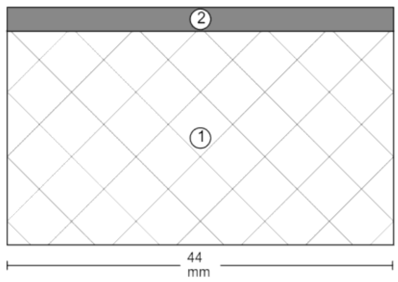
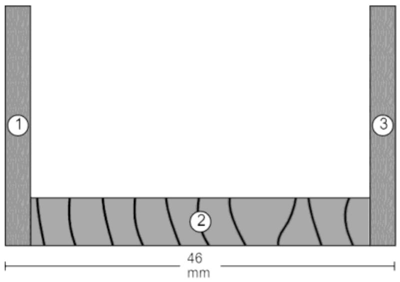
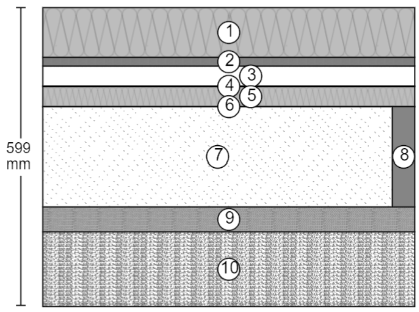
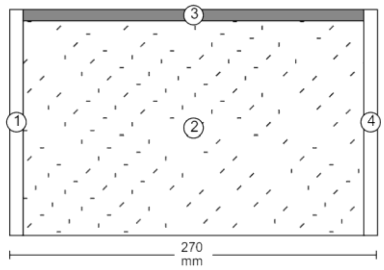
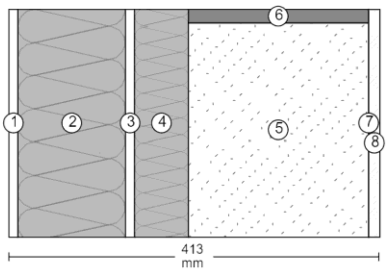
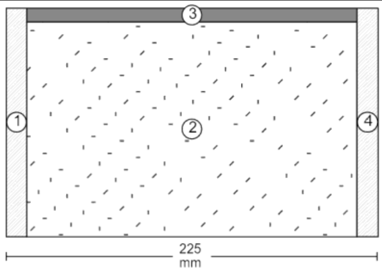
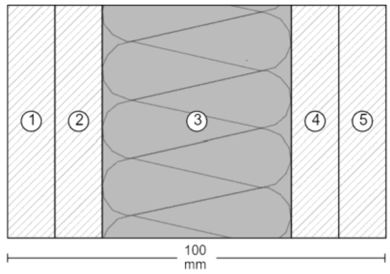
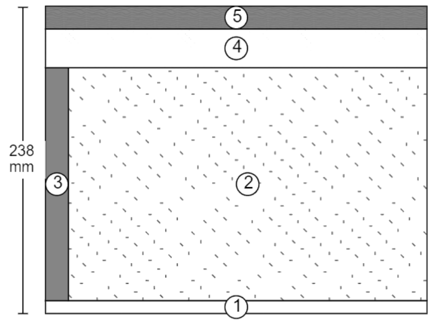
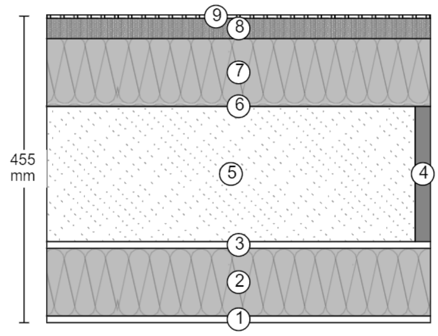
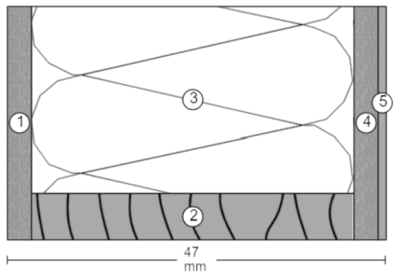
		-Window handle, 1 piece
Glass doors and windows		1. Insulated glazing, double pane, 24.00mm 2. Aluminium mullion-transom system, 24.00mm Additional: -frame profiles for doors - Verband Fenster + Fassade - frame profile for doors made of (stainless) steel, 6 m -Joint sealing strips, butyl, 6 m -Fenster-Beschlag für Drehkippfenster, 1 piece -Window handle, 1 piece
Interior doors		1. Laminated veneer board, 3.00mm 2. Glued laminated timber - straight shapes (German average), 40.00mm 3. Laminated veneer board, 3.00mm Additional: -Window handle, 1 piece

Table 4. Renovated Building Scenario components

Flooring + foundation (Ground floor)		**1. Mineral wool (floor insulation), 100.00mm** 2. Solid wood parquet (German average), 17.60mm 3. Cement screed, 40.00mm 4. PE foil, dimpled, 1.25mm 5. Mineral wool (floor insulation), 40.00mm 6. Damp insulation PA, 0.20mm 7. Ready-mix concrete C20/25, 200.00mm 8. Reinforcement steel wire, 200.00mm 9. Sand 0/2, 50.00mm 10. Gravel (Grain size 2/32), 150.00mm
Exterior non load-bearing wall		1. Rendering mortar – Reinforcement Fibre Plaster, 10.00mm 2. Ready-mix concrete C20/25, 250.00mm 3. Reinforcement steel wire, 250.00mm 4. Rendering mortar – Reinforcement Fibre Plaster, 10.00mm
Exterior load-bearing wall		**1. Mineral pre-made mortar: rendering mortar – Reinforcement Fibre Plaster, 10.00mm** **2. Mineral wool (facade insulation), 120.00mm** 3. Mineral pre-made mortar: rendering mortar – Reinforcement Fibre Plaster, 10.00mm 4. Mineral wool (facade insulation), 60.00mm 5. Ready-mix concrete C20/25, 200.00mm 6. Reinforcement steel wire, 200.00mm 7. Damp insulation PA, 0.10mm 8. Gypsum plaster board (fire protection) (12.5 mm), 12.50mm

Load-bearing interior walls		1. Gypsum plaster board (fire protection) (12.5 mm), 12.50mm 2. Ready-mix concrete C20/25, 200.00mm 3. Reinforcement steel wire, 200.00mm 4. Gypsum plaster board (fire protection) (12.5 mm), 12.50mm
Non load-bearing interior walls		1. Gypsum plaster board (perforated board) (12.5 mm), 12.50mm 2. Gypsum plaster board (impregnated, moisture resistant) (12.5 mm), 12.50mm 3. Mineral wool (partition walls insulation), 50.00mm 4. Gypsum plaster board (impregnated, moisture resistant) (12.5 mm), 12.50mm 5. Gypsum plaster board (fire protection) (12.5 mm), 12.50mm
Ceiling Structure		1. Mineral pre-made mortar: rendering and plastering mortar – normal/finishing render or plaster, 10.00mm 2. Ready-mix concrete C20/25, 180.00mm 3. Reinforcement steel wire, 180.00mm 4. Cement screed, 30.00mm5Solid wood parquet (German average), 17.60mm
Roof Structure		**1. Mineral pre-made mortar: rendering and plastering mortar – normal/finishing render or plaster, 10.00mm** **2. Mineral wool (flat roof insulation), 100.00mm** 3. Mineral pre-made mortar: rendering and plastering mortar – normal/finishing render or plaster, 10.00mm 4. Reinforcement steel wire, 200.00mm 5. Ready-mix concrete C20/25, 200.00mm 6. Bitumen sheets G 200 S4, 0.20mm 7. Mineral wool (flat roof insulation), 100.00mm 8. Gravel (Grain size 2/32), 30.00mm 9. EPDM roof sheets, 5.00mm
Exterior Doors		1. Laminated veneer board, 3.00mm 2. Glued laminated timber - straight shapes (German average), 40.00mm 3. Mineral wool (partition walls insulation), 40.00mm 4. Laminated veneer board, 3.00mm 5. Steel sheet (0.3-30mm), 1.00mm Additional: -frame profiles for doors - Verband Fenster + Fassade - frame profile for fire control doors made of (stainless) steel, 6 m -Joint sealing strips, butyl, 8 m -Window handle, 1 piece

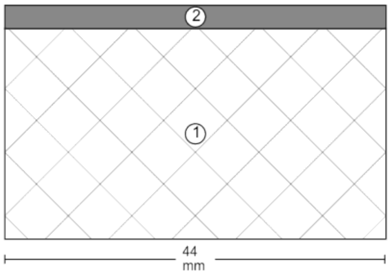
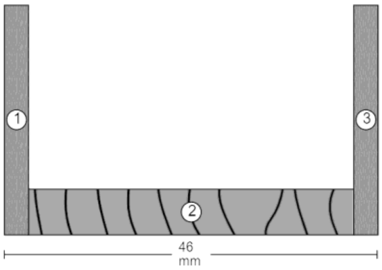
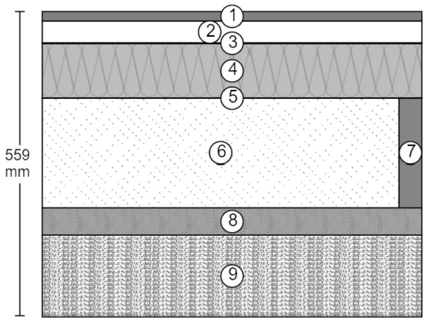
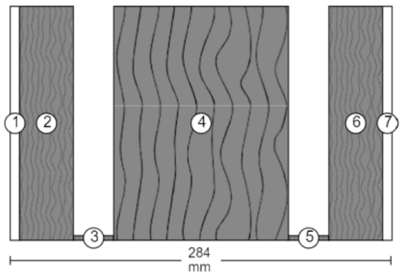
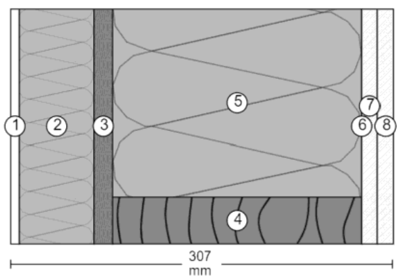
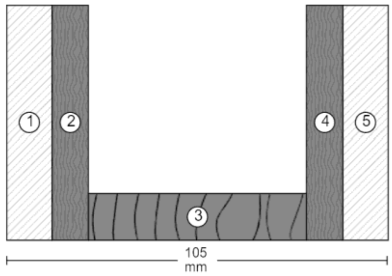
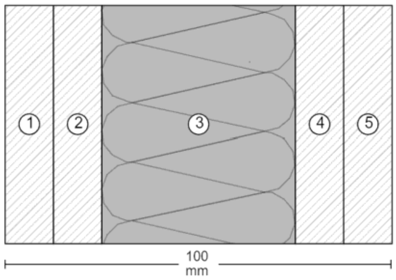
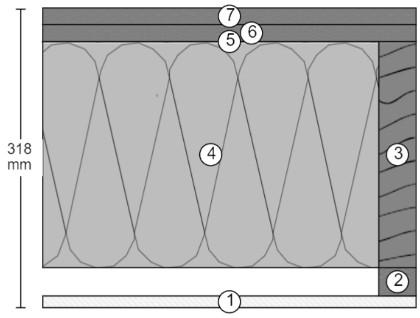
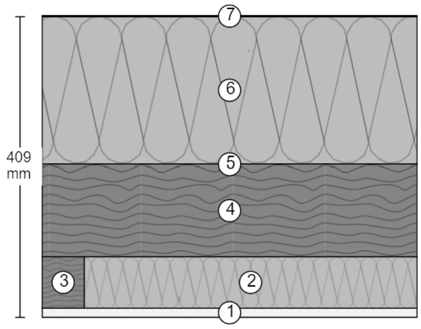
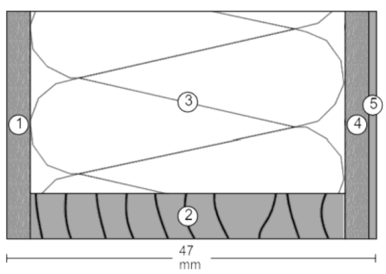
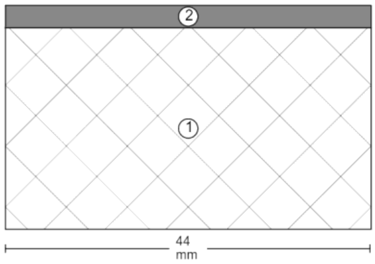
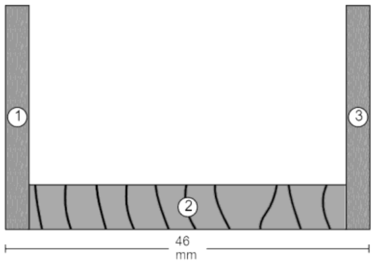
Glass doors and windows		**1. Insulated glazing, triple pane, 44.00mm** 2. Aluminium mullion-transom system, 44.00mm Additional: -frame profiles for doors - Verband Fenster + Fassade - frame profile for doors made of (stainless) steel, 6 m -Joint sealing strips, butyl, 6 m -Fenster-Beschlag für Drehkippfenster, 1 piece -Window handle, 1 piece
Interior doors		1. Laminated veneer board, 3.00mm 2. Glued laminated timber - straight shapes (German average), 40.00mm 3. Laminated veneer board, 3.00mm Additional: Window handle, 1 piece

Table 5. New Building Scenario components

Flooring + foundation (Ground floor)		1. Solid wood parquet (German average), 17.60mm 2. Cement screed, 40.00mm 3. PE foil, dimpled, 1.25mm 4. Mineral wool (floor insulation), 100.00mm 5. Damp insulation PA, 0.20mm 6. Ready-mix concrete C20/25, 200.00mm 7. Reinforcement steel wire, 200.00mm 8. Sand 0/2, 50.00mm 9. Gravel (Grain size 2/32), 150.00mm
Exterior non load-bearing wall		1. Rendering mortar – Reinforcement Fibre Plaster, 7.00mm 2. Cross laminated timber, 40.00mm 3. Cross laminated timber, 30.00mm 4. binderholz CLT BBS, 130.00mm 5. Cross laminated timber, 30.00mm 6. Cross laminated timber, 40.00mm 7. Rendering mortar – Reinforcement Fibre Plaster, 7.00mm
Exterior load-bearing wall		1. Mineral pre-made mortar: rendering mortar – Reinforcement Fibre Plaster, 7.00mm 2. Wood fibre insulation boards, 60.00mm 3. Medium Density Fibreboard, 15.00mm 4. KVH structural timber (German average), 200.00mm 5. Mineral wool (partition walls insulation), 200.00mm 6. Damp insulation PA, 0.10mm 7. Gypsum plaster board (impregnated, moisture resistant) (12.5 mm), 12.50mm 8. Gypsum plaster board (fire protection) (12.5 mm), 12.50mm

Load-bearing interior walls		1. Gypsum plaster board (fire protection) (12.5 mm), 12.50mm 2. EGGER OSB boards, 10.00mm 3. KVH structural timber (German average), 60.00mm 4. EGGER OSB boards, 10.00mm 5. Gypsum plaster board (fire protection) (12.5 mm), 12.50mm
Non load-bearing interior walls		1. Gypsum plaster board (perforated board) (12.5 mm), 12.50mm 2. Gypsum plaster board (impregnated, moisture resistant) (12.5 mm), 12.50mm 3. Mineral wool (partition walls insulation), 50.00mm 4. Gypsum plaster board (impregnated, moisture resistant) (12.5 mm), 12.50mm 5. Gypsum plaster board (fire protection) (12.5 mm), 12.50mm
Ceiling Structure		1. Gypsum plaster board (fire protection) (12.5 mm), 12.50mm 2. Cross laminated timber, 30.00mm 3. KVH structural timber (German average), 240.00mm 4. Mineral wool (flat roof insulation), 240.00mm 5. EPDM-Dach- und Dichtungsbahnen EVALASTIC®V,VG,VSGK, 0.10mm 6. Plywood board, 18.00mm 7. Solid wood parquet (German average), 17.60mm
Roof Structure		1. Gypsum fibre board (10 mm), 12.50mm 2. Mineral wool insulation (medium bulk density range), 70.00mm 3. KVH structural timber (German average), 70.00mm 4. Cross laminated timber (German average), 125.00mm 5. Damp insulation PE, 0.20mm 6. Mineral wool insulation (medium bulk density range), 200.00mm 7. EPDM roof sheets, 1.50mm
Exterior Doors		1. Laminated veneer board, 3.00mm 2. Glued laminated timber - straight shapes (German average), 40.00mm 3. Mineral wool (partition walls insulation), 40.00mm 4. Laminated veneer board, 3.00mm 5. Steel sheet (0.3-30mm), 1.00mm Additional: -frame profiles for doors - Verband Fenster + Fassade - frame profile for fire control doors made of (stainless) steel, 6 m -Joint sealing strips, butyl, 8 m -Window handle, 1 piece

Glass doors and windows		1. Insulated glazing, triple pane, 44.00mm 2. Aluminium mullion-transom system, 44.00mm Additional: -frame profiles for doors - Verband Fenster + Fassade - frame profile for doors made of (stainless) steel, 6 m -Joint sealing strips, butyl, 6 m -Fenster-Beschlag für Drehkippfenster, 1 piece -Window handle, 1 piece
Interior doors		1. Laminated veneer board, 3.00mm 2. Glued laminated timber - straight shapes (German average), 40.00mm 3. Laminated veneer board, 3.00mm Additional: -Window handle, 1 piece

4. Results

Figure 11 presents the Overall exergy impact (OExI) calculated for each scenario, illustrating the contributions from materials in terms of Chemical Exergy Consumption of Materials (CExC-M), energy in terms of Resource Exergy Consumption of Energy (RExC-E) and Primary Exergy Consumption of Energy (PExC-E) , and emissions in terms of Chemical Exergy of Emissions (CExE). It should be mentioned that combining CExC-M and the PExC-E in definition, yields the cumulative exergy for materials. But these two are reported separately throughout this work for methodological clarity.

The results reveal that the "New" scenario exhibits the highest OExI, while the "Renovated" scenario yields the lowest. With respect to category contributions, RExC-E together with PExC-E consistently dominate the overall results across all scenarios (as seen in Figure 12). Although both the renovated and new scenarios demonstrate lower CExE compared to the old scenario, the absolute magnitude of exergy associated with emissions remains very small. Consequently, this category has a negligible effect on the OExI outcome.

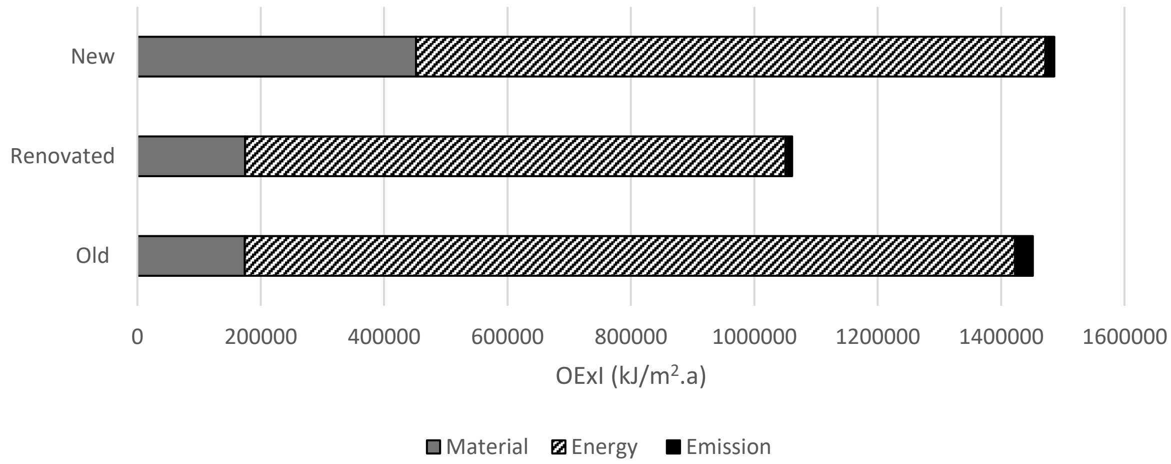


Figure 11. Overall Exergy Impact (OExI) of three scenarios (*own illustration)*

Table 6. Exergy values of three scenarios in three categories

	CExC-M kJ/m^2.a	RExC-E+ PExC-E kJ/m^2.a	CExE kJ/m^2.a
Old	174 357.62	1 247 933.94	29 390.36
Renovated	174 854.79	875 764.07	10 852.52
New	451 550.15	1 020 367.65	14 392.25

A notable difference is observed in the CExC-M between scenarios, reflecting the calculation methodology. As explained in the methodology section, the remaining embodied burden from the old building is added to the renovated and new scenarios to ensure comparability, meaning the differences do not indicate inherently lower impacts of old materials.

When comparing the new scenario without the compensation for the old building's remaining burden (277,192.53 kJ/m^2·a) to twice the value of the old scenario (2 × 174,358 = 348,716 kJ/m^2·a), the new wooden building yields approximately 71,000 kJ/m^2·a lower CExC-M than the concrete building. It should be noted that these results could differ if insulation materials were included in the exergy calculations, particularly given that the quantity of mineral wool used in the new building is higher than in the old scenario. This aspect warrants further exploration in future research.

These findings underscore the critical role that scenario definition plays in determining outcomes. While the passage of time reduces the remaining embodied burden of a building, this effect applies equally to all three scenarios, meaning the relative differences between the new and renovated scenarios remain consistent.

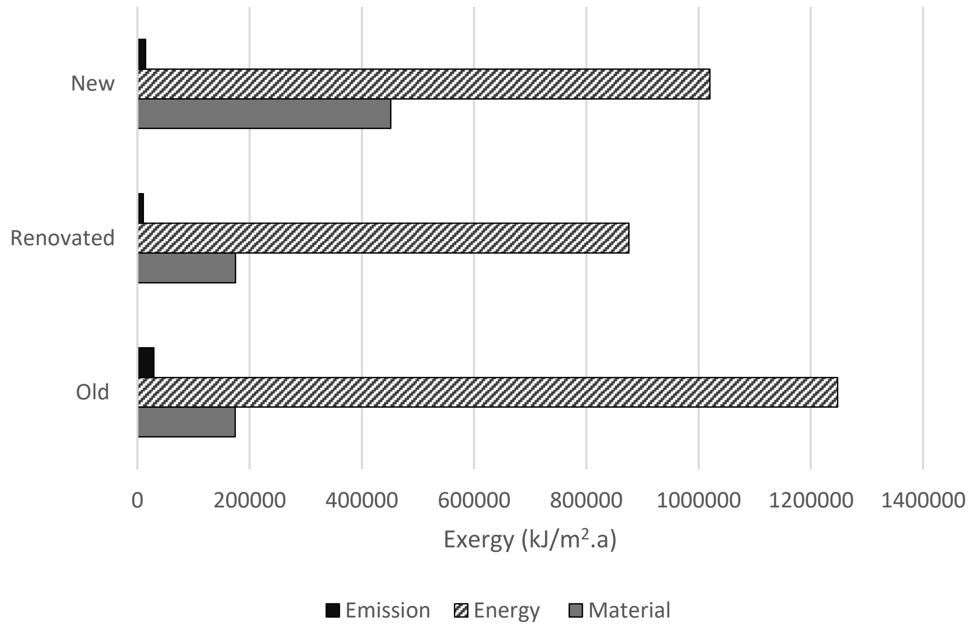


Figure 12. Comparison of the contribution of different exergy categories in three scenarios (*own illustration)*

Another observation is that the CExE represents a very small fraction of the total exergy consumption—typically below 3% of the combination of RExC-E+ PExC-E. This low contribution can be attributed to the methodological limitation that only the chemical exergy of emissions was considered, without accounting for downstream exergy effects such as the thermodynamic implications of the greenhouse gas effect, radiative forcing, or ecosystem disruption caused by these emissions. This limitation highlights a critical learning for future development of exergy-based LCA methodologies: downstream exergy effects must be systematically included to achieve a comprehensive and thermodynamically consistent assessment.

Figure 13 illustrates the breakdown of OExI for each scenario, highlighting the contributions from CExC-M, RExC-E, PExC-E and CExE subcategories. In all three cases, RExC-E is clearly the dominant factor in overall exergetic impact. In the renovated scenario, the CExC-M share increases, as expected, due to the assumptions of adding materials for upgrades, mainly insulation and triple glazing. This increase however, shown in table 6, is minor (0.29%), as insulation chemical exergy was excluded from the calculations due to lack of data, rendering the effect negligible. Future studies should estimate this value, even if only approximately, to prevent underestimation.

In the new-build scenario, CExC-M surpasses that of the other cases, reflecting the significant environmental burden imposed by constructing an entirely new structure. Notably, the increase in CExC-M is not fully offset by the reduction in RExC-E, resulting in a higher OExI for the new scenario compared to both the renovated and old cases, as depicted in Figure 14. It should also be noted that the calculation does not include material consumption associated with building services, such as those used in the creation of heating systems, due to data and software limitations. Including this aspect in future studies could provide further insights and potentially affect the comparative results.

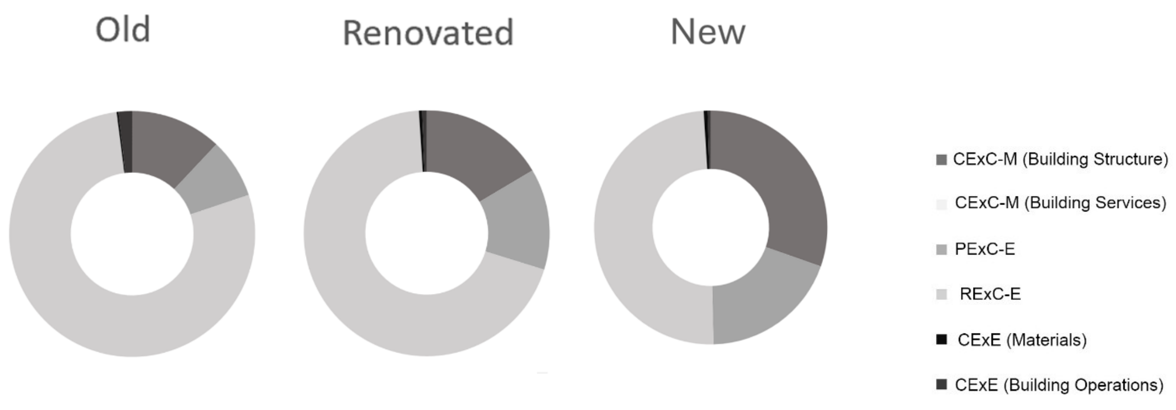


Figure 13. Contribution of six exergy categories to the OExI of each scenario (*own illustration)*

Table 7. Quantities of six exergy categories in three scenarios

	CExC-M (Building Structure) kJ/m^2.a	CExC-M (Building services) kJ/m^2.a	PExC-E kJ/m^2.a	RExC-E kJ/m^2.a	CExE (Materials) kJ/m^2.a	CExE(Building operation) kJ/m^2.a
Old	174 357.62	-	113 933.94	1 134 000	3 638.93	25 751.43
Renovated	174 854.79	-	141 364.07	734 400	4 593.50	6 259.03
New	451 550.15	-	285 967.65	734 400	8 133.22	6 259.03

Even though the CExC-M results for the renovated scenario do not fully represent all impacts, Table 7 shows a substantial 24% increase in PExC-E, indicating the high energy intensity of manufacturing and processing glass and insulation materials. This is also reflected in material-related CExE increase of 77% in this scenario.

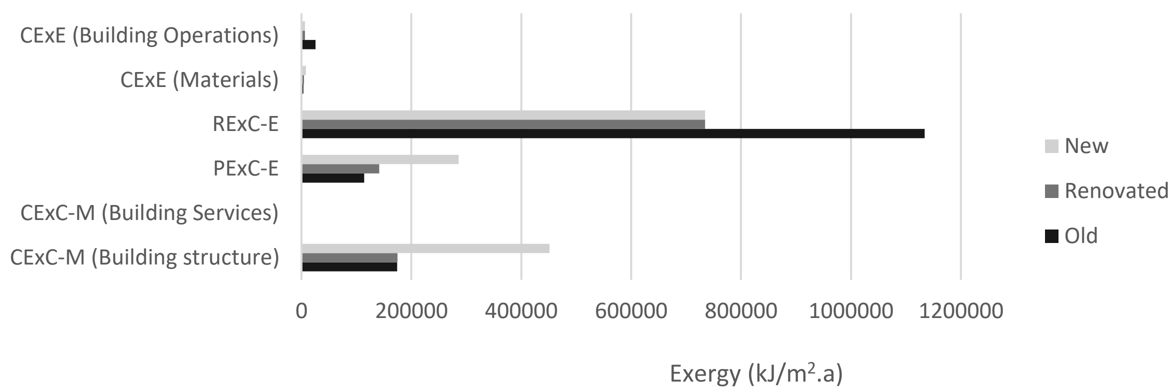


Figure 14. Comparison of each scenario in terms of six exergy categories (*own illustration)*

Figure 15 presents the distribution of chemical exergy among individual materials used in the building envelope for each scenario. The results indicate that steel consistently contributes the largest share to CExC-M across all scenarios. This predominance is primarily associated with the steel reinforcement bars embedded in concrete structural elements. In the original and renovated scenarios, the high shares of both steel and concrete are expected outcomes, given the concrete structure of the reference building. In the new-build scenario, the major contribution from steel and concrete is mainly attributed to the reinforced concrete slab foundation. These findings highlight the significant impact of structural material choices, particularly steel and concrete, on the overall exergetic impact of building structures.

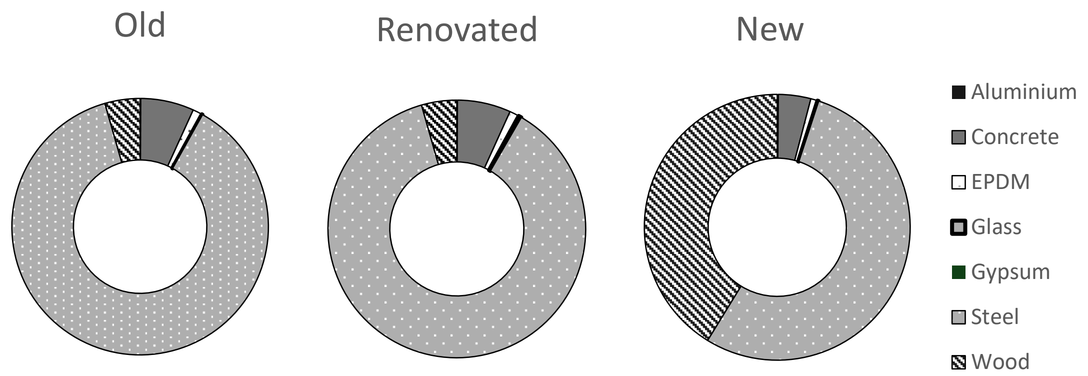


Figure 15. Contribution of different materials to CExC-M for building structure category (*own illustration)*

An important aspect highlighted by this analysis is the influence of original material quantities on the total CExC-M. As shown in Table 10, concrete constitutes the largest mass fraction among primary building materials, about five times greater than steel. Nevertheless, steel ultimately accounts for the largest share of total CExC-M, exceeding that of concrete by a factor of 13. This outcome reflects the definition and calculation of material exergy: the much higher chemical exergy value reported for steel (see Table 9) is due to steel's highly reactive and separated state relative to the natural environment, which requires considerable useful work for its production. In contrast, concrete is composed mainly of chemically stable compounds (such as calcium silicate hydrate) that are closer to equilibrium with Earth's reference environment, resulting in a much lower chemical exergy. Thus, a material like steel, with a chemical exergy of 34.64 MJ/kg, is substantially more "thermodynamically distant" from nature than concrete (0.54 MJ/kg), indicating both the greater resource intensity of its production and its potential to do work if allowed to revert to equilibrium. The implications of materials with high exergy contributions will be analyzed further in Section 4.1, “Sensitivity Analysis.”

Table 8. Quantities of different materials to CExC-M in three scenarios

Exergy (kJ/m^2.a)		
Old	Renovated	New

Aluminium	133.41	133.41	590.67
Concrete	11 718.08	11 718.07	17 810.00
EPDM	2 077.78	2 077.78	3 681.41
Glass	169.78	666.95	666.95
Gypsum	2.36	2.36	63.97
Steel	152 522.20	152 522.17	242 618.84
Wood	7 734.02	7 734.02	186 118.28

Table 9. Standard Chemical exergy values SCExM of different materials

Material Chemical Exergy (MJ/kg)						
Aluminium	Concrete	EPDM	Glass	Gypsum	Steel	Wood
29.49	0.54	48.04	5.20	0.15	34.64	31.23

Table 10. Reference quantities of materials in kg used in old scenario

Reference material quantity (kg/m^2.a)- Old scenario						
Aluminium	Concrete	EPDM	Glass	Gypsum	Steel	Wood
0.01	43.40	0.09	0.07	0.03	8.81	0.50

Figure 16 depicts the CExE resulting from both material and energy consumption for each scenario. The exergy associated with each emission is calculated by multiplying the chemical exergy value of each substance by its emitted quantity. In the life cycle assessment outputs, emissions are typically presented as equivalents relative to a specific reference substance or composition for each impact category, for example, global warming potential (GWP) is provided in kg CO_2-equivalent, even though the actual emissions include substances such as CH_4 and N_2O, among others. Due to limited access to detailed compositional emission data and for methodological simplicity, the exergy for each LCA indicator is estimated by multiplying the respective kg substance equivalent by the standard chemical exergy value of that reference substance. As a result, the reported exergy values represent approximate, order-of-magnitude figures and should be interpreted as rough estimates.

The most prominent trend in all scenarios is the substantially higher exergy associated with the global warming potential category compared to other emission categories. Specifically, the GWP exergy exceeds other material-related emissions by a factor of 38–46, and surpasses other energy-related emissions by up to 126 times in the old scenario, and by up to 23 times in the renovated and new scenarios. The exergy associated with ozone depletion potential (ODP, kg CFC-11-eq) and abiotic depletion potential of elements (ADP elem., kg Sb-eq) is so low as to be negligible in graphical representations. Quantitative results provided in Table 11 indicate that, in the old scenario, energy-related CO_2 emissions account for an CExE value approximately seven times greater than that of material-related emissions. This difference narrows to a factor of 1.3 in the renovated scenario, and reverses in the new scenario, where the new construction materials results in emissions with 1.3 times higher CExE than those from operational energy. It should be noted that downstream effects of emissions were not modeled in this study due to their substantial methodological complexity; however, given that the results demonstrate CExE contributes minimally compared to CExC-M and RExC-E, future research should prioritize developing methods to quantify these downstream impacts for a more comprehensive assessment.

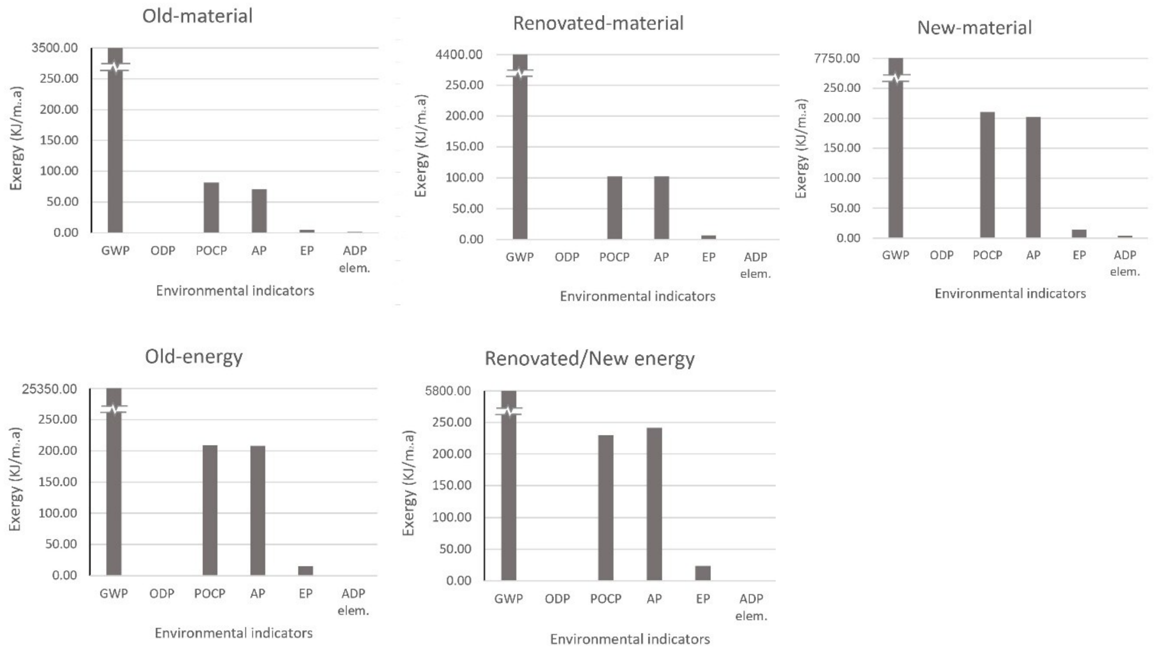


Figure 16. CExE (kJ/m².a) caused by material and energy consumption for different scenarios (*own illustration)*

Table 11. Quantities of CExE for different scenarios

	Old-material kJ/m².a	Renovated-material kJ/m².a	New-material kJ/m².a	Old-energy kJ/m².a	Renovated-energy kJ/m².a	New-energy kJ/m².a
GWP	3 481.62	4 380.55	7 703.03	25 319.38	5 764.22	5 764.22
ODP	0.00	0.00	0.00	0.00	0.00	0.00
POCP	81.13	102.36	210.40	208.61	229.83	229.83
AP	70.21	102.48	201.53	208.15	241.59	241.59
EP	4.85	6.96	14.24	15.22	23.29	23.29
ADP elem.	1.12	1.15	4.02	0.08	0.09	0.09

Figure 17 analyzes the results for exergy associated with different energy consumption types including RExC-E and PExC-E throughout the building life cycle. Operational energy, including heating, hot water, lighting, and equipment, accounts for one category (RExC-E), while embodied energy, comprising the energy required for material production and other life cycle processes associated with that, forms the other (PExC-E). Across all scenarios, exergy associated with heating and hot water systems as part of RExC-E overwhelmingly dominates results.

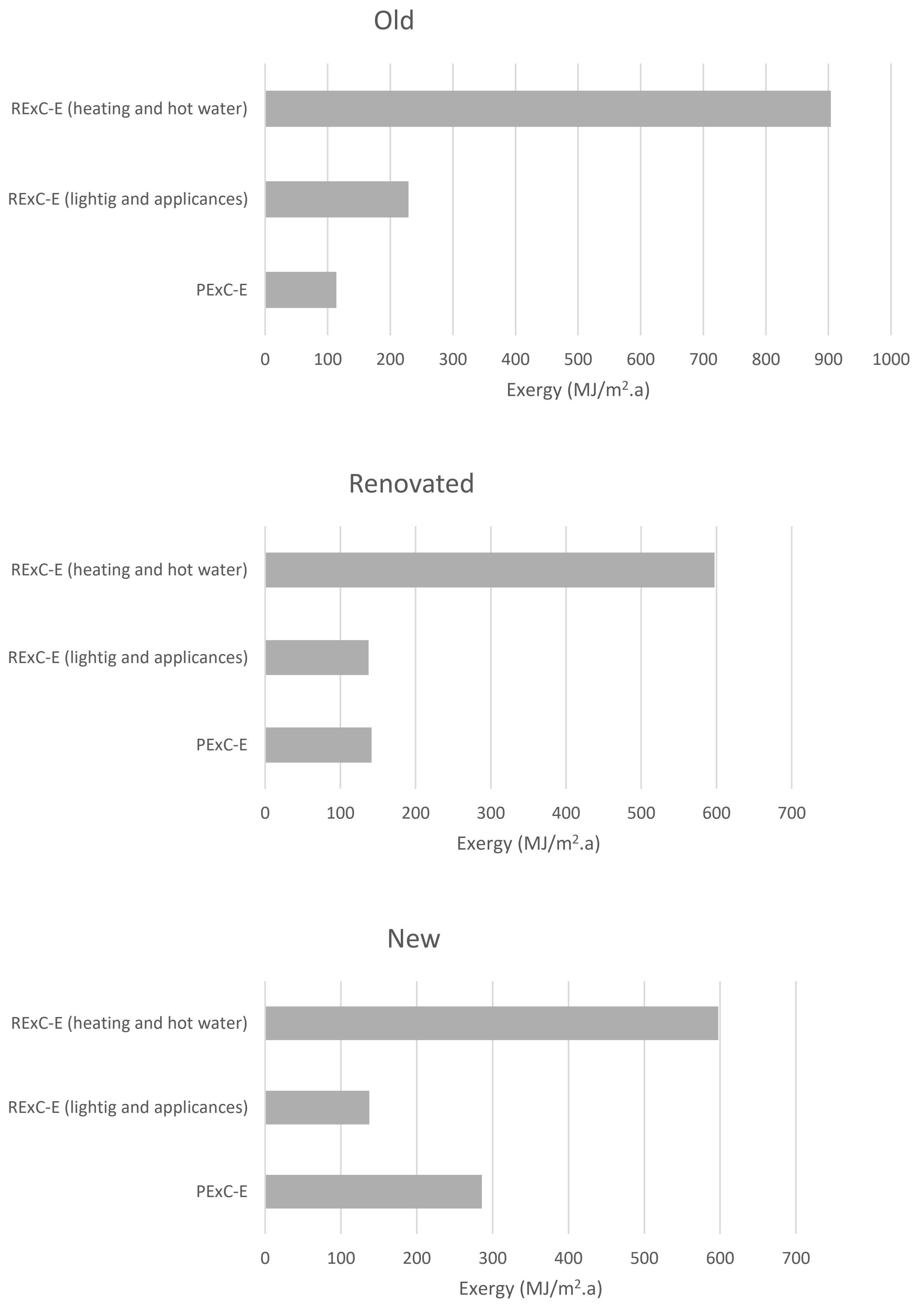


Figure 17. Share of different categories in total energy-related exergies (*own illustration)*

Table 12. Exergy values of different energy consumption categories

	PExC-E MJ/m^2.a	RExC-E (lightig and applicances) MJ/m^2.a	RExC-E (heating and hot water)* MJ/m^2.a
Old	113.93	228.96	903.78
Renovated	141.36	137.37	597.52
New	285.96	137.37	597.52

*Heating system in old scenario is considered as a low temperature gas boiler, and for the renovated and new scenarios as pellet boiler

In the old scenario, heating is provided by a low-temperature gas boiler utilizing natural gas, a non-renewable energy source, whereas the renovated and new scenarios employ pellet boilers that use renewable fuel. The RExC-E for heating and hot water in the renovated and new scenarios is approximately 33.3% lower compared to the old scenario, mirroring a 28.9% reduction in original energy demand (from 149 to 106 units). This consistency highlights that exergy analysis reliably traces thermodynamic quality and useful work potential, but does not directly reflect renewability or environmental impact [52]; This is of course as long as downstream effects of emissions are excluded from exergy analysis.

Additionally, the reduced RExC-E for lighting and appliances in the renovated and new scenarios reflect the influence of efficient system upgrades. The accuracy of the exergy calculations for energy consumption is further explored and validated in Section 4.2, "Validation."

4.1. Sensitivity Analysis:

A targeted sensitivity analysis was performed to identify key parameters with significant influence on OExI outcomes and practical relevance for intervention. Among all building materials, steel and concrete were found to be the dominant contributors to CExC-M in every scenario (see Figure 15). Notably, the building foundation, constructed from reinforced concrete, is assumed identical across all scenarios, and contains a substantial proportion of both concrete and steel relative to total material consumption.

To investigate the impact of foundation assumptions, an alternative version of the new-build scenario was modeled, wherein the original building's foundation is retained and refurbished rather than fully reconstructed. In this alternative, both the direct and indirect exergy impacts associated with foundation materials (concrete and steel) are excluded from the life cycle assessment of the new scenario. Comparative charts illustrate the impact of this modification on OExI and relevant subcategories (Figures 18 and 19).

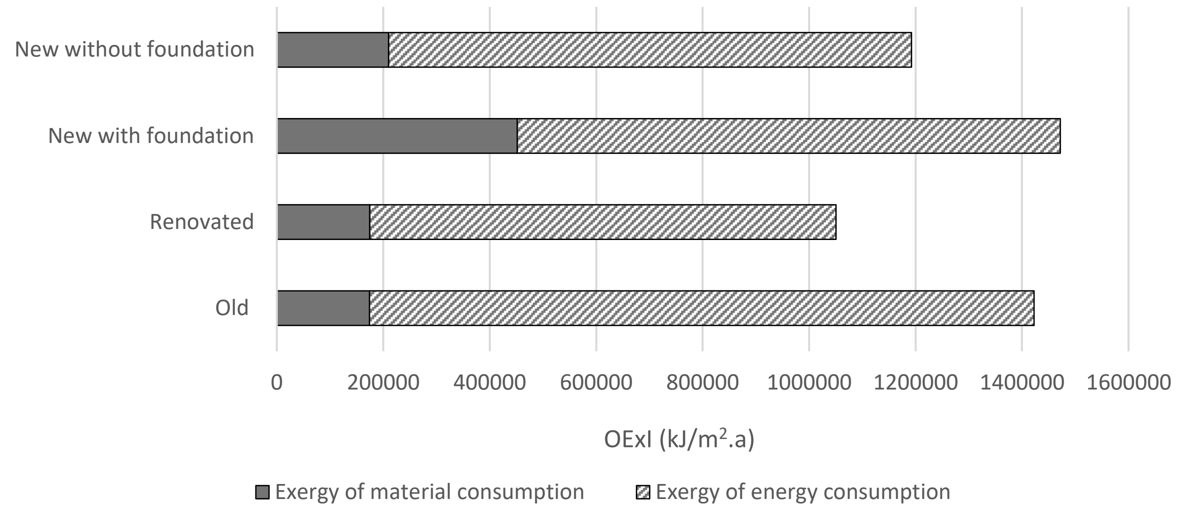


Figure 18. Comparison of the OExI of New without foundation scenario with three original scenarios (*own illustration)*

Table 13. Quantities of exergy for four scenarios in Material and energy consumption categories

	CExC-M kJ/m².a	RExC-E+ PExC-E kJ/m².a	RExC-E kJ/m².a	PExC-E kJ/m².a
Old	174 357.60	1 247 934.00	1 134 000.00	113 933.94
Renovated	174 854.80	875 764.10	734 400.00	141 364.10
New with foundation	451 550.20	1 020 368.00	734 400.00	285 967.00
New without foundation	210 288.20	981 921.00	734 400.00	247 521.00

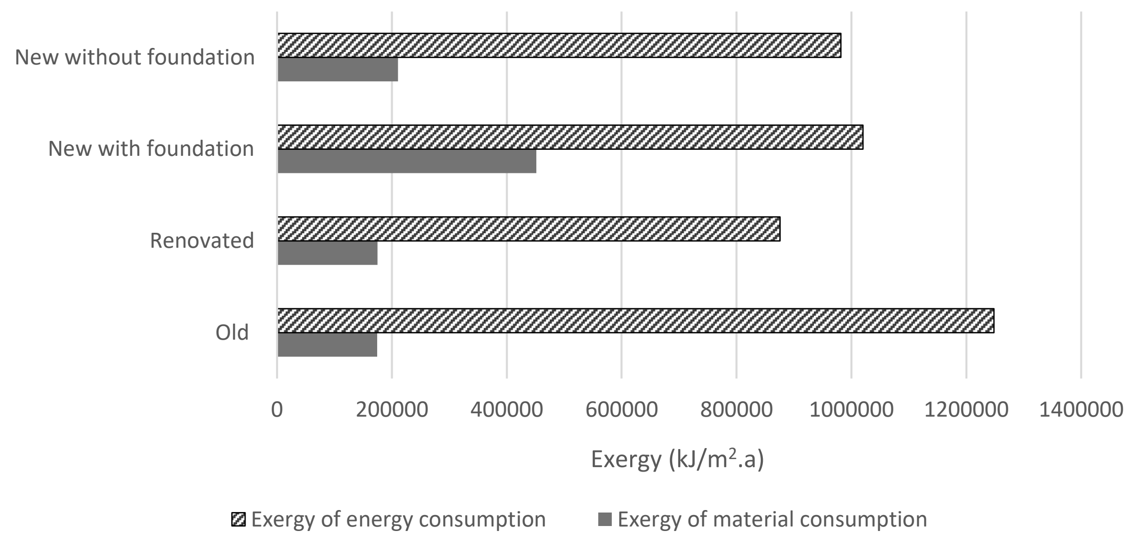


Figure 19. Comparison of exergies in material and energy consumption categories for four scenarios (*own illustration)*

The results in Figure 18 reveal that omitting the foundation from the new-build scenario results in a reduction of OExI by 19%. More specifically, this adjustment leads to a 53% decrease in CExC-M of building structure and a 13% reduction in PExC-E. With these revisions, the OExI of the revised new scenario drops below that of the old scenario, yet still remains higher than the renovated scenario. As a result, building renovation continues to represent the most effective strategy for minimizing OExI per square meter per year.

4.2. Validation of Results

The RExC-E, as presented in the results section, was primarily determined using the Resource Exergy Analysis (REA, Method 1) in conjunction with the Exergy Pass tool. To validate these results and assess the robustness of methodological choices, two additional exergy calculation approaches were applied to the operational energy stage.

Method 2: Multiplying primary energy indicators (PERE/PENRE) by exergy quality factors (β-values) from literature sources (Kotas, Michalakakis) [55][56]. These indicators (PERE and PENRE) are typically calculated within LCA software using the Cumulative Energy Demand (CED) methodology [54] and distinguish between renewable and non-renewable primary energy use. Exergy values are obtained by multiplying the PERE and PENRE results by the recommended β-values for each relevant energy carrier. This approach utilizes exergy-to-energy conversion factors rather than full cumulative exergy demand calculations. The quality factors represent the ratio of chemical exergy to lower heating value (LHV) for each fuel type, enabling simplified conversion of primary energy to exergy equivalents.

-Variation 1: Uses ratios from Kotas [55]

- Variation 2: Utilizes ratios from Michalakakis, a more recent source [56]

Method 3: calculates exergy based on Szargut's Cumulative Exergy Content (CExC) values [46], directly applying the energy demand values to the exergy coefficients for each fuel type (e.g., 1.06 for natural gas, 3.4 for electricity).

Table 14. Exergy to energy ratios and CExC for different energy sources

	Natural Gas	Wood	Electricity
Exergy b exergy/LHV (kotas) [55]	1.04 J/J LHV	1.15 J/J LHV	1 J/J
Exergy b exergy/LHV (Michalakakis) [56]	1.02 J/J LHV	1.04 J/J LHV	-
CExC (Szargut) [46]	1.06 H_L	-	3.40 J/J

Table 15. Exergies calculated for building operational energy consumption for old scenario in three methods

	Old Scenario (Total) MJ/m^2.a	Renovated/ New Scenario (Total) MJ/m^2.a
Method 1* (Main Method)	1 134.00	734.40
Method 2-V. 1*	1 004.41	946.01
Method 2-V. 2*	991.51	877.71
Method 3*	989.24	-

* Method 1: Resource Exergy Analysis (REA) [39], Method 2-variation 1: using Lca indicators and exergy to energy ratio from Kotas [55], Method 2-Variation 2: using Lca indicators and exergy to energy ratio from Michalakakis [56], Method 3: Using Final energy demand and CExC from Szargut [46],

As shown in Table 15, Notably, REA produces higher exergy values for the old scenario and more pronounced differentiation between the scenarios, whereas variation 1 of Method 2 results in smaller differences across scenarios and a notably higher value for the renovated/new scenario compared to Method 1. These differences are primarily attributable to how each method accounts for upstream losses and applies conversion factors.

REA considers upstream losses, capturing all resource exergy consumed throughout the supply chain. This results in higher overall exergy values and more accurate reflection of true thermodynamic resource consumption. In contrast, Methods 2 variations 1 and 2 primarily provide exergy-to-lower heating value (LHV) ratios but neglect upstream losses, leading to systematically lower exergy estimates. This is the key difference driving the observed divergence in results. The variation between Kotas and Michalakakis factors reflects differences in their underlying chemical exergy data sources and assumptions, with Method 2-Variation 1 (Kotas) producing higher estimates due to higher quality factors.

Method 3 (CExC) does consider upstream losses, but these are significantly lower than those calculated by REA. This discrepancy accounts for the substantial difference in exergy values between REA and CExC, even though both methods attempt to capture supply-chain impacts.

REA is judged to provide the most thermodynamically rigorous and context-sensitive results for this building exergy analysis. The observed differences among methods underscore the critical importance of methodological selection and highlight how simplifications in exergy accounting can substantially influence comparative conclusions. These findings reinforce the necessity for transparent methodological reporting

4.3. Recommendation and Discussion

As detailed in the methodology section, this study assumes the reference building was originally constructed in 1999. At the reference year 2025, two practical future pathways are evaluated: either renovating the building while retaining the main structure and core components, or demolishing and rebuilding with updated materials and systems. An important modeling assumption is that, since life cycle calculations for the original building are based on a 50-year lifespan, the year 2025 falls before this notional lifetime ends. As such, a portion of the environmental burden associated with material use and production processes remains “unfulfilled” and must be allocated to subsequent interventions.

To maintain methodological consistency, the environmental impact attributed to this remaining service life (the unexpired portion from 2025 onward) is numerically added to burdens from renovation or reconstruction. Thus, the comparative results in Section 4.1 reflect a 50-year analysis period (2025–2075), and scenario impacts are distributed as follows:

1. Old Scenario: The building is retained with no significant upgrades to components or services. Only 50% of the material-related impacts, proportionate to the unexpired service life, are considered. The subsequent period (2049–2075) is assumed impact-free for non-recurring impacts (i.e., materials), with operational (use-phase) environmental impacts assessed continuously for the full 50 years.
2. Renovated Scenario: The building's primary structure is maintained, but efficiency improvements are implemented. Key interventions include: (a) additional insulation to major heat loss surfaces (roof, exterior walls, ground floor); (b) replacement of double glazing with triple glazing for windows/glass doors; (c) improved airtightness and reduction of thermal bridges (accounted for via reduced heating demand); (d) upgrading to more efficient lighting and equipment; and (e) replacement of the old gas boiler with a pellet boiler. In this scenario, the environmental impacts from added renovation materials and operational improvements are combined with the remaining material life cycle impacts (reflecting the share of the old building not yet expended at the point of renovation).
3. New-Build Scenario: Full demolition of the old building is assumed, followed by new construction employing improved components, higher-performance insulation, energy-efficient lighting and equipment, and renewable pellet-based heating. The majority of the envelope and structure is assumed to utilize wood and modern, optimized materials for minimized operational impact. As with the renovation case, the remaining environmental burden of the old building's unexpired lifespan is included to avoid misallocation of unfulfilled impacts.

The results show that the renovated scenario yields the lowest OExI across the evaluation period. Compared to the old scenario, the renovated building benefits from significantly reduced RExC-E demonstrating that upgrading heating systems and building fabric before a building reaches its nominal end of life can substantially reduce environmental impacts for the remainder of its lifecycle.

For the new-build scenario, the OExI result is relatively close to that of the old building, despite notable improvements in the RExC-E. The higher overall value in this scenario reflects a greater contribution from CExC-M, as a substantial portion of the old building's unfulfilled material burden is transferred to the new structure. This suggests a strong opportunity to further reduce impacts by timing replacement closer to the actual end of the original building's service life, or alternatively, by retaining and reusing major elements such as the foundation—a strategy shown, in sensitivity analyses, to markedly improve the performance of the new-build option. These findings are considered expectable, as the energy demand and supply systems were assumed to be the same for both renovated and new scenarios, with the main difference being the higher material consumption in the new scenario.

Ultimately, the findings confirm that the lower material input of the renovated scenario, having lower material input compared to the new construction, results in reduced exergetic and environmental burdens over the studied period, given that operational energy demand remains consistent across scenarios. A key finding of this study is that renovation—specifically focused on upgrading the heating system and improving the building envelope to reduce operational energy demand—can be environmentally and exergetically beneficial even before the end of the building's original service life. In this case, renovation after only 25 years of operation proved advantageous.

Additionally, the comparative analysis reveals the substantial contribution of the foundation to the overall material exergy consumption. Foundations represent a significant portion of the CExC-M and RExC-E in both old and new construction scenarios due to their mass and the resource-intensive materials involved (primarily concrete and steel reinforcement). Retaining the existing foundation when constructing a new building—rather than demolishing and rebuilding it—could provide a valuable contribution to impact reduction by avoiding the exergy and environmental costs associated with new foundation materials and construction processes.

These findings collectively illustrate how scope decisions—such as foundation reuse, the timing of renovation interventions, and the definition of system boundaries—can significantly influence comparative outcomes in life cycle assessments. Such decisions should be carefully considered and transparently reported to ensure that results reflect real environmental trade-offs.

5. Uncertainty and Limitations

Methodological limitations play a central role in this research and are addressed in detail in Section 2.3.7 ("Methodological Limitations"). The following section provides an overview of the principal uncertainties and limitations encountered throughout this thesis.

Methodological Integration Constraints in This Research

The integration of exergy assessment into the LCA framework for this thesis inherits uncertainties from both methodologies. The manual data entry process for the eLCA software introduced potential transcription errors, and material flow quantifications relied on assumptions regarding component specifications. Furthermore, this study was constrained by eLCA's predefined use of EN 15804 standardization, which determined the characterization factors and impact category calculations affecting all downstream PERE, PENRE, and emission indicator results. Additionally, the static energy grid composition modeled in the eLCA database does not account for annual variations in electricity mix, potentially misrepresenting the actual energy supply profile across the 60-year study period.

Scenario Definition Constraints Affecting Interpretability

The temporal scope definition in this thesis—comparing existing, renovated, and new construction scenarios—significantly influences results. Altering the renovation timing within the building's assumed lifetime would yield substantially different exergy outcomes. More critically, the original research question and scenario definitions inadvertently constrained the comparative analysis: because both the renovated and new scenarios were assigned identical operational energy demands and supplied by the same heating system, the new scenario's higher material consumption resulted in a largely predetermined conclusion that total exergy demand would be greater. This outcome emerged from scenario boundary conditions rather than from genuine comparative performance differences. For future refinements of this framework, scenarios should be defined with competing operational or material efficiency advantages to generate more decision-relevant insights.

Case Study-Specific Data Limitations

This thesis relied on an existing building with incomplete historical documentation. Missing component specifications—particularly precise layering and original construction details—necessitated assumptions formulated using contemporary best-practice standards and available component templates. Results therefore represent the designed renovation and new construction scenarios rather than absolute reconstructions of actual building conditions, introducing scenario-specific uncertainties that limit generalization to other building typologies.

Methodological Heterogeneity in Exergy Quantification

A significant limitation of this study is the reliance on three distinct methodological approaches for different exergy categories within a single assessment. The REA (Resource Exergy Analysis) method was employed for operational energy exergy because it rigorously differentiates storable from non-storable resources. However, REA application via available online tools was restricted to operational phases, requiring the alternative primary energy conversion method (multiplying PERE/PENRE by β factors) for material production energy exergy. Material chemical exergy values were sourced from published literature and integrated with production energy exergy to quantify cumulative material demand. Emission chemical exergy was calculated separately using substance-specific standard values. This methodological pluralism creates internal inconsistencies: the REA method and primary energy conversion approach employ different reference environment assumptions and resource categorizations, undermining direct comparability between operational and material-related exergy results reported in this thesis. Harmonizing these approaches across all exergy categories would strengthen the integrated assessment but exceeded the scope of this proof-of-concept study.

6. Conclusion

The research findings demonstrate that renovation emerges as the most effective strategy for minimizing exergetic and environmental burdens over the 50-year evaluation period (2025–2075), significantly outperforming both old and new-build alternatives. This conclusion is driven not by arbitrary value judgments but by fundamental thermodynamic principles embedded in the exergy-based assessment framework.

The renovated scenario yields the lowest Overall Exergy Impact (OExI) by strategically reducing operational energy demand through heating system upgrades and envelope improvements. Critically, this finding reveals that building envelope upgrades undertaken before nominal end-of-life can substantially reduce cumulative environmental impacts, challenging conventional assumptions that early intervention necessarily increases total burden.

In contrast, the new-build scenario demonstrates markedly reduced Resource Exergy Consumption of Energy (RExC-E) but incurs substantial material exergy (CExC-M) penalties from initial construction. This scenario reveals the thermodynamic cost of complete reconstruction: while new building systems operate more efficiently, the concentrated material and energy inputs required for new construction substantially offset operational gains over the studied timeframe. Significantly, retaining and reusing major structural elements—particularly foundations—substantially improves new-build performance, indicating that foundation preservation represents exceptional thermodynamic value for residential building typologies.

The old scenario serves as baseline reference, demonstrating that maintaining the existing building without intervention results in moderate total impacts dominated by operational energy consumption across the 50-year period.

Critical Reflection on Methodological Approach

This thesis presents an important proof-of-concept demonstration: exergy-based life cycle assessment enables comprehensive physical resource accounting without requiring arbitrary weighting factors. Unlike conventional LCA approaches dependent on subjective impact category weightings, exergy provides an objective thermodynamic basis for comparing diverse environmental burdens—material depletion, energy consumption, and emissions—within a unified framework.

However, methodological limitations warrant explicit acknowledgment. This study did not consistently account for downstream environmental effects of emissions (e.g., acid rain formation, eutrophication, bioaccumulation), representing a significant scope limitation in the exergy assessment of emission impacts. Additionally, the integration of three distinct methodological approaches (REA for operations, primary energy conversion for material production, literature-derived chemical exergy for materials) created internal inconsistencies regarding reference environments and resource categorizations. These inconsistencies, acknowledged in Sections 2.3.7 and 5, suggest that conclusions comparing material,emission, and operational exergy domains should be interpreted with appropriate methodological caveats.

Practical Implications for Building Strategy

From a practical standpoint, this thesis supports renovation of existing buildings as the thermodynamically optimal strategy for residential building stock. The findings indicate that early intervention to upgrade building envelopes and heating systems before end-of-life substantially outperforms complete reconstruction, both from operational and cumulative exergy perspectives. For smaller residential buildings with valuable structural elements (particularly foundations), this advantage is particularly pronounced, as retained structural components represent concentrated thermodynamic value relative to new construction requirements.

7. Outlook

Despite the limitations, this thesis demonstrates that exergy-based LCA should be further developed as a foundational framework for building sustainability assessment. The thermodynamic rigor of exergy analysis—particularly the REA method's distinction between storable and non-storable resources—provides conceptual advantages over simplified energy-based approaches. The challenge for future research lies in synthesizing this thermodynamic comprehensiveness with practical applicability.

A refined methodological framework could emerge from coupling REA principles with comprehensive substance-level inventory data (e.g., ecoinvent, GaBi databases) and systematic accounting of material flow transformations throughout life cycles. Such an approach would address current limitations regarding downstream environmental fate modeling and emissions specification while maintaining exergy's fundamental advantage: providing objective, thermodynamically grounded resource impact assessment without subjective weighting schemes.

Recommendation for future development: An enhanced exergy-based LCA methodology—integrating REA rigor with complete substance accounting and downstream impact pathways—could substantially advance building sustainability assessment, providing a physically defensible alternative to conventional characterization-factor-dependent approaches. This thesis contributes to that development trajectory by demonstrating proof-of-concept feasibility and identifying the specific methodological refinements required for comprehensive application.

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Appendix

Table 16. Values of the standard chemical exergy of emissions, SCExE, for GWP gases. [16]

Greenhouse Gas	SCExE (kJ/mol)	Molar Mass (g/mol)	SCExE in kg/MJ
CO_2	19.80	44.01	2.22
CH_4	831.90	16.04	0.02
N_2O	106.40	44.01	0.41
CFC-11	577.90	137.37	0.24
CFC-12	599.40	120.91	0.20
HFC-23	622.60	70.01	0.11
HCFC-22	644.50	86.47	0.13
PFC-116	1077.80	138.01	0.13
NF_3	667.10	71.00	0.11
SF_6	728.20	146.06	0.20
Total for units of global warming potential (kg/MJ)			3.77

Table 17. Standard Chemical exergy of emission substances [46]

Substance	State	Standard Chemical Exergy kJ/mol
CO_2	g	$19.87b_{ch\,n}$
C_2H_4	g, ethylene	$1361.1b_{ch\,n}$
SO_2	g	$313.4\ b_{ch\,n}$
H_3PO_4	$3H^+$, PO_4^{3-} (dissociated)	$204.4\ b^{\circ}_{ch}$
Sb	s	$438.1b^{\circ}_{ch}$

Table 18. Standard Chemical Exergies of Material (SCExM) [16]

Material Name	Material Chemical Exergy (MJ/kg)
Aluminum	29.49
Brick	0.18
Ceramic	0.19
Concrete	0.54
EPDM	48.04
Epoxy coating	36.18
Fiberglass	0.59
Glass	5.20
Gypsum	0.15
HDPE	48.50
Hollow core/mortar	0.40
Paint (acrylic)	39.30
Paint (silicone)	39.28
Polyurethane foam	36.61
Steel	34.64
Wallpaper	70.53
Wood	31.23

Table 19. Calculated exergies for materials and fuels and their comparison to previous sources [44]

Material	Calculated exergy	Reference exergy	Relative difference	Reference
Inorganic materials				
Aggregate	500 kJ/kg	620 kJ/kg	16%	(Koroneos et al., 2012)

Aluminum	29 000 kJ/kg	32 900 kJ/kg	12%	(Kotas, 1995)
Cement	1 100 kJ/kg	1 000 kJ/kg	10%	(Ari, 2011)
Copper	2 100 kJ/kg	2 100 kJ/kg	0%	(Kotas, 1995)
Limestone	60 kJ/kg	60 kJ/kg	0%	(Morris & Szargut, 1986)
Steel	7 100 kJ/kg	6 800 kJ/kg	4%	(Szargut, 2005)
Zinc	5 400 kJ/kg	5 400 kJ/kg	0%	(Kotas, 1995)
				Organic materials
General biomass	21 000 kJ/kg	20 200 kJ/kg	4%	(Song et al., 2011)
Paper	17 000 kJ/kg	20 200 kJ/kg	16%	(Song et al., 2011)
Thermoplastics	35 000 kJ/kg	38 900 kJ/kg	10%	(Eboh et al., 2016)
Thermosets	23 000 kJ/kg	20 800 kJ/kg	9%	(Eboh et al., 2016)
Wood	20 500 kJ/kg	20 800 kJ/kg	1%	(Song et al., 2011)
	1.04 J/J LHV	1.11 J/J LHV	6%	(Kotas, 1995)
		Organic fuels		
Coal	1.01 J/J LHV	1.04 J/J LHV	3%	(Kotas, 1995)
Crude oil	46 600 kJ/kg	44 800 kJ/kg	4%	(Kotas, 1995)
	1.02 J/J LHV	1.06 J/J LHV	4%	(Kotas, 1995)
Natural gas	1.02 J/J LHV	1.04 J/J LHV	2%	(Kotas, 1995)
Oil products	1.04 J/J LHV	1.06 J/J LHV	2%	(Kotas, 1995)

Table 20. Typical values of φ (ratio of the standard chemical exergy of a fuel to its lower heating value (LHV)) for some industrial fuels and other combustible substances [55]

Fuel	**$\varphi=\varepsilon^0/(NCV)^0$**
Coke	1.05
Different types of coal	1.06-1.10
Peat	1.16
Wood	1.15-1.30
Different fuel oils and petrol	1.04-1.08
Natural gas	1.04 ± 0.5%
Coal gas	1.00 ± 1%
Blast furnace gas	0.98 ± 1%
Hydrogen	0.985
Carbon monoxide	0.973
Sulphur (rhombic)	2.017

Table 21. Values of Cumulative Exergy Content (CExC) and Cumulative Exergy Efficiency (CExE) [46]

Material		**Units in Columns 2, 4**	**CEXC**	**CEXE %**	**Notes**
Name	**Exergy b**				
1	2	3	4	5	6
Bituminous coal	1.09 H_L	MJ/kg	1.12 H_L	93.1	
Lignite	1.17 H_L	MJ/kg	1.20 H_L	92.3	
Metallurgical Coke	1.06 H_L	MJ/kg	1.35 H_L	74.2	
Natural gas	1.04 H_L	MJ/kmol	1.06 H_L	91.5	high CH_4 content
Gasoline	1.07 H_L	MJ/kg	1.32 H_L	80.8	
Electricity	1	J/J	3.40	29.4	from bituminous

* H_L= lower heating value

Table 22. The value gathered from REA for RExC-E of old Scenario[39]

Demand name	Energy quality (demand)	Energy quality (supply)	Energy demand (of total scenario)	External energy losses (of total scenario)	Energy demand (of line)	External energy losses (of line)	Resource efficiency	Resource consumption	CO2e emissions
	%	%	%	%	kWh	kWh	%	kWh	kg
					/ m2*a			/ m2*a	
Space heat	4,43	100,00	64,25	44,00	115,00	78,76	2,63	193.76	37,69
Electric.	100,00	100,00	16,76	18,77	30,00	33,60	47,17	63.6	0,57
Hot water	6,41	100,00	18,99	13,01	34,00	23,29	3,81	57.29	11,14

Table 23. The value gathered from REA for RExC-E of renovated/new Scenario[39]

Demand name	Energy quality (demand)	Energy quality (supply)	Energy demand (of total scenario)	External energy losses (of total scenario)	Energy demand (of line)	External energy losses (of line)	Resource efficiency	Resource consumption	CO2e emissions
	%	%	%	%	kWh	kWh	%	kWh	kg
					/ m2*a			/ m2*a	
Space heat	4,43	100,00	40,22	22,76	72,00	40,74	2,83	112.74	1,08
Electric.	100,00	100,00	10,06	11,26	18,00	20,16	47,17	38.16	0,34
Hot water	6,41	100,00	18,99	10,75	34,00	19,24	4,10	53.24	0,51

Table 24. .Total material quantities and respective CExC-M for each- old scenario

Material	Quantity (kg)	Material Chemical exergy (MJ/kg)	Total Exergy MJ
Aluminium	114.91	29.49	3 388.69
Concrete	551 183.67	0.54	297 639.18
EPDM	1 098.58	48.04	52 775.78
Glass	829.35	5.20	4 312.62
Gypsum	6 114	0.15	917.1
Steel	111 837.85	34.64	3 874 063.12
Wood	6 290.24	31.23	196 444.19
Mineral Wool	4 072.31	-	-
Gravel	89 610.30	-	-
Cement Screed	44 945.28	-	-
Sand	21 797.10	-	-
Mineral pre-made mortar	10 057.6	-	-

* The reported values in result section are converted to the reference unit (total/m^2.a)

Table 25. Total material quantities and respective CExC-M for each- Renovated scenario

Material	Quantity (kg)	Material Chemical exergy (MJ/kg)	Total Exergy MJ
Aluminium	0	29.49	0
Concrete	0	0.54	0
EPDM	0	48.04	0
Glass	1 214.24	5.20	6 314.04
Gypsum	0	0.15	0
Steel	0	34.64	0
Wood	0	31.23	0
Mineral Wool	6 511.2	-	-
Gravel	0	-	-
Cement Screed	0	-	-
Sand	0	-	-
Mineral pre-made mortar	0	-	-

* The reported values in result section are converted to the reference unit (total/m^2.a)

Table 26. Total material quantities and respective CExC-M for each-new scenario

Material	Quantity (kg)	Material Chemical exergy (MJ/kg)	Total Exergy MJ
Aluminium	196.92	29.49	5 807.17
Concrete	143 273.15	0.54	77 367.50
EPDM	423.94	48.04	20 366.07
Glass	1 214.24	5.20	6 314.04
Gypsum	12 867.00	0.15	1 930.05
Steel	33 031.98	34.64	1 144 227.78
Wood	72 541.79	31.23	2 265 480.10
Mineral Wool	13 907.85	-	-
Gravel	89 610.30	-	-
Cement Screed	31 000.32	-	-
Sand	21 797.10	-	-
Mineral pre-made mortar	3 370.30	-	-

* The reported values in result section are converted to the reference unit (total/m^2.a)

Table 27. Primary energy consumption gathered from eLCA calculations for each scenario used for the calculation of PExC-E

	Old-material	Renovated-material	New-material
PENRE (MJ/m^2.a)	161.90	23.92	110.05
PERE (MJ/m^2.a)	65.95	3.50	61.97

* The reported values in result section are converted to respond to the defined scenarios' service life

Table 28. Emission Indicator values gathered from eLCA calculations for each scenario

Indicator	Unit	Old-material	Renovated-material	New-material	Old-energy	Renovated/New -energy
GWP	kg CO2 equiv.	15.42	1.99	9.35	56.07	12.76
ODP	kg R11 equiv.	3.55 E-09	1.23 E-09	3.32 E-08	6.86 E-12	4.49 E-12

POCP	kg ethene equiv.	0.003	0.0004	0.002	0.004	0.004
AP	kg SO2 eqv.	0.02	0.006	0.02	0.04	0.04
EP	kg PO4 equiv.	0.004	0.0009	0.004	0.007	0.01
ADP elem.	kg Sb equiv.	0.0006	7.31797E-06	0.0008	2.24 E-05	2.39 E-05

* The quantities are reported in this table according to reference unit (total/m^2.a)