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Revealing the interplay between decarbonisation, circularity, and cost-effectiveness in building energy renovation

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Building energy renovation mitigates carbon emissions but often increases material demand and financial costs. This work addresses this problem by investigating the carbon, material, and economic footprints of various renovation scenarios in the Dutch residential sector from 2015 to 2050. Results show that, compared to the baseline, façade refurbishment could lower cumulative lifecycle emissions by up to 0.3%, while raising material use by 21–25% and costs by 2–6%. Sensitivity analysis indicates that refurbishing the heating system offers greater potential for reducing carbon emissions. Rebuilding could cut emissions by up to 17% under an ambitious energy transition, though this would triple material use and construction costs. Circularity strategies could offset up to 89% of the material footprint and reduce carbon emissions by up to 23%. Nonetheless, considerable cost increases from renovations remain inevitable, even with advanced material circulation systems, suggesting circular renovation strategies with enhanced incentives as concerted action.

The combined problems of escalating resource depletion, waste generation, and the pressing need to curb greenhouse gas (GHG) emissions necessitate a paradigm shift towards a more sustainable development pathway. Circular economy and low-carbon economy stand out as two prominent sustainable economic modes, intricately interconnected, yet each focuses on distinct aspects. The circular economy emphasises the efficient use of resources by promoting a closed-loop system where materials are reduced, reused, and recycled rather than discarded after use[1]. The low-carbon economy primarily targets the reduction of GHG emissions to mitigate climate change and its adverse effects by transitioning away from fossil fuels and adopting renewable energy sources[2]. The built environment emerges as a pivotal battleground for the circular and low-carbon campaigns, as it is responsible for 50% of raw material use, 40% of total energy use, 40% of waste generation, and 35% of GHG emissions[3]. Furthermore, despite efforts to circulate construction and demolition waste (CDW), the global built environment continues expanding, thereby sustaining an increasing demand for primary materials[4]. In 2023, recovered material only comprised 11.8% of the total material used in Europe, reflecting only a marginal increase of 1.1 percentage points since 2010[5]. Adding to these challenges, most of the building stock is not energy-efficient[6]. The European Union (EU) faces the fact that 97% of its buildings require energy renovation to attain a decarbonised building stock by 2050[7].

Pursuing circularity and decarbonisation during the transition to a sustainable built environment may lead to conflicting objectives. As evidenced by current practices, recycling CDW, while contributing to circularity, could inadvertently result in higher GHG emissions than

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using virgin material[8–11]. Conversely, the ongoing building energy renovation, aimed at decarbonisation, may also exacerbate resource depletion and waste generation[12–14]. Therefore, efficient material circulation is increasingly necessary for achieving carbon neutrality[15]. Moreover, to unlock the potential for financial savings, the European Commission (EC) also stipulates that member states must adopt a cost-optimal approach to building energy renovation[6,16], further heightening its complexity.

Relevant research investigated the trade-offs between economic and environmental profiles[17–22], embodied and operational impacts[12,23–30], and material- and energy-based implications in building energy renovation[13,29]. Nevertheless, the myth concerning the 'decarbonisation vs. circularity vs. cost-effectiveness' persists, as previous studies rarely address the superposed effect of various circularity strategies, renewable energy advancements, and energy price volatilities on building energy renovations from a life cycle perspective. This is particularly noteworthy in the face of recent events such as the EU's ambitious circularity[15] and clean energy[31] transitions, as well as the surge of energy prices in Europe resulting from the Russo-Ukrainian War[32].

The Netherlands reflects the prevailing situation of the built environment in the EU—a high recovery rate of CDW with a substantial inventory of energy-inefficient and ageing buildings. The Netherlands achieved 92% recovery rates for CDW in 1995 and 97% in 2018[33]. However, over 90% of the CDW is being downcycled as backfill for road foundation and site elevation[34]. To enhance the material efficiency in, amongst others, the construction sector, the Netherlands has launched the programme A Circular Economy in the Netherlands by 2050 to promote high-quality material circulation[3]. On the other hand, around half of the buildings in the Netherlands were constructed between the 1950s and 1970s, before the introduction of minimum energy performance requirements in 1995, leading to inefficient energy use for heating and cooling purposes[35]. In the 2019 Climate Agreement, the Netherlands has established an intermediate goal of achieving a 49% reduction in GHG emissions by 2030 relative to 1990 levels, alongside a long-term ambition of attaining a 95% reduction[36]. Consequently, the GHG emissions from the built environment are expected to reduce from 29.9 Mt CO_2-eq in 1990 to 15.3 Mt CO_2-eq by 2030 and 1.5 Mt CO_2-eq by 2050[37,38]. The residential sector dominates the built environment in terms of floor area (80%), final energy use (70%), and carbon emission (60%)[39]. This further implies that, by 2050, 80% of the 7.5 million dwellings (170,000 annually) would undergo renovation to a nearly zero-energy building level[35]. Therefore, the Netherlands is a representative case study, offering valuable insights into sustainable building energy renovation within the broader European context.

Here, we develop an integrated model combining a dynamic material flow analysis (dMFA) with a lifecycle-based footprint analysis to unveil the trade-offs and synergies in attaining decarbonisation, circularity, and cost-effectiveness across various renovation options for the Dutch housing sector from 2015 to 2050. Three energy renovation scenarios are established: a Baseline (BsL) scenario without additional renovation effort, a Rebuild (ReB) scenario involving the demolition and reconstruction of all old homes, and a Refurbishment (ReF) scenario focused on adding additional cladding to the exterior walls of old homes. We use lifecycle GHG emissions (in kg CO_2-eq), Total Material Requirement (in kg)[40], and financial costs (in €) as indicators to present the carbon, material, and economic footprints, respectively. The unitary footprints for constructing, refurbishing, operating and demolishing per square metre of home are calculated by life cycle assessment (LCA) and life cycle costing (LCC). They are then scaled up to the national level by coupling to the sizes of stocks and flows quantified by the dMFA.

Rebuilding and refurbishment are supported by a prefabricated concrete element (PCE) system developed as part of the H2020 project VEEP[41]. It includes two types of PCEs: one designed for constructing walls in new homes across all scenarios and another specifically aimed at recladding the exterior façades of old homes in the ReF scenario. To assess their responses to different socioeconomic and political contexts, we construct and superimpose different interventions on the three energy renovation scenarios as follows: (i) Material Circulation Strategies, concerning maintaining the current High Recovery (HR) approach or shifting to Enhanced Circularity (EC) practice; (ii) Energy Transition Pathways, representing two levels of clean energy penetration to limit the global temperature increase to 3.5 °C and 1.5 °C, respectively; (iii) Power Price Trends, illustrating the potential impact of the Russo-Ukrainian War and the subsequent decisions regarding the import of pipeline gas from Russia on electricity and gas prices in Europe, encompassing two states of the Russia-Europe relations: Relief (Rf) and Tensions (Ts). Specifically, material circulation strategies would determine the management route of CDW at the end-of-life (EoL) stage, energy transition pathways would influence the energy used throughout all life cycle stages of a building, and power price trends would impact energy utility costs during the operation stage. Based on the estimated footprint profiles of each renovation scenario, the study further offers policy recommendations to promote the sustainable development of the built environment in Europe.

Results

Housing stocks and material flows

The dMFA model investigates the housing stock, material inflows and waste outflows from the Dutch residential sector under three scenarios, as illustrated in Fig. 1. The analysis spans the timeframe from 2015 to 2050, concluding at the end of the discrete-year interval. Figure 1a shows that the BsL and ReF scenarios maintain consistent construction and demolition floor areas annually, determined by the projected EoL homes within the existing housing stock. The ReB scenario exhibits a notably higher construction and demolition floor area owing to extensive reconstruction since 2015. In the ReF scenario, the yearly refurbishment of the floor area remains constant, as shown in Fig. 1b. Contrasting with the refurbishment approach, in the ReB scenario, an equal quantity of old homes undergoes demolition ahead of schedule and subsequent reconstruction. As a result, by 2050, residences built before 2015 would be replaced. Both refurbishment and rebuilding begin with the oldest vintage cohorts. Nevertheless, the three scenarios remain equivalent regarding net housing stock per year.

Figure 1c illustrates the raw materials employed and waste generated across the three scenarios. Mineral materials, including concrete, brick, glass, and gypsum, constitute over 90% of the total material used and waste generation across all scenarios. In the BsL scenario, cumulative material demand reaches ~425 Mt, surpassing its CDW generation of 261 Mt. The ReF scenario exhibits slightly higher cumulative material demand and waste generation, totalling 588 Mt and 281 Mt, respectively. The ReB scenario, however, demonstrates substantially greater cumulative material demand at ~1259 Mt, with CDW generation exceeding material demand and reaching around 1483 Mt. This highlights the potential of the ReB scenario to circulate CDW as a feedstock, effectively meeting raw material demand even under extensive reconstruction efforts.

Figure 2a–c shows the cumulative amount of material demand and waste management in the three energy renovation scenarios across two material circulation strategies. In all scenarios, waste concrete is the primary CDW stream. Despite substantial rebuilding and refurbishment efforts, wastes from demolition activities dominate as the largest CDW streams, constituting over 90% of the total CDW in three scenarios. In the context of HR practices, 87–88% of the CDW generated between 2015 and 2050 undergoes primarily downcycling, whereas the overall recycling rate of CDW stands at only 7–8%. In the more advanced EC practice, a noticeable portion of downcycled CDW is gradually redirected towards high-value-added treatment operations. This results in enhanced recycling, upcycling, and reuse rates for

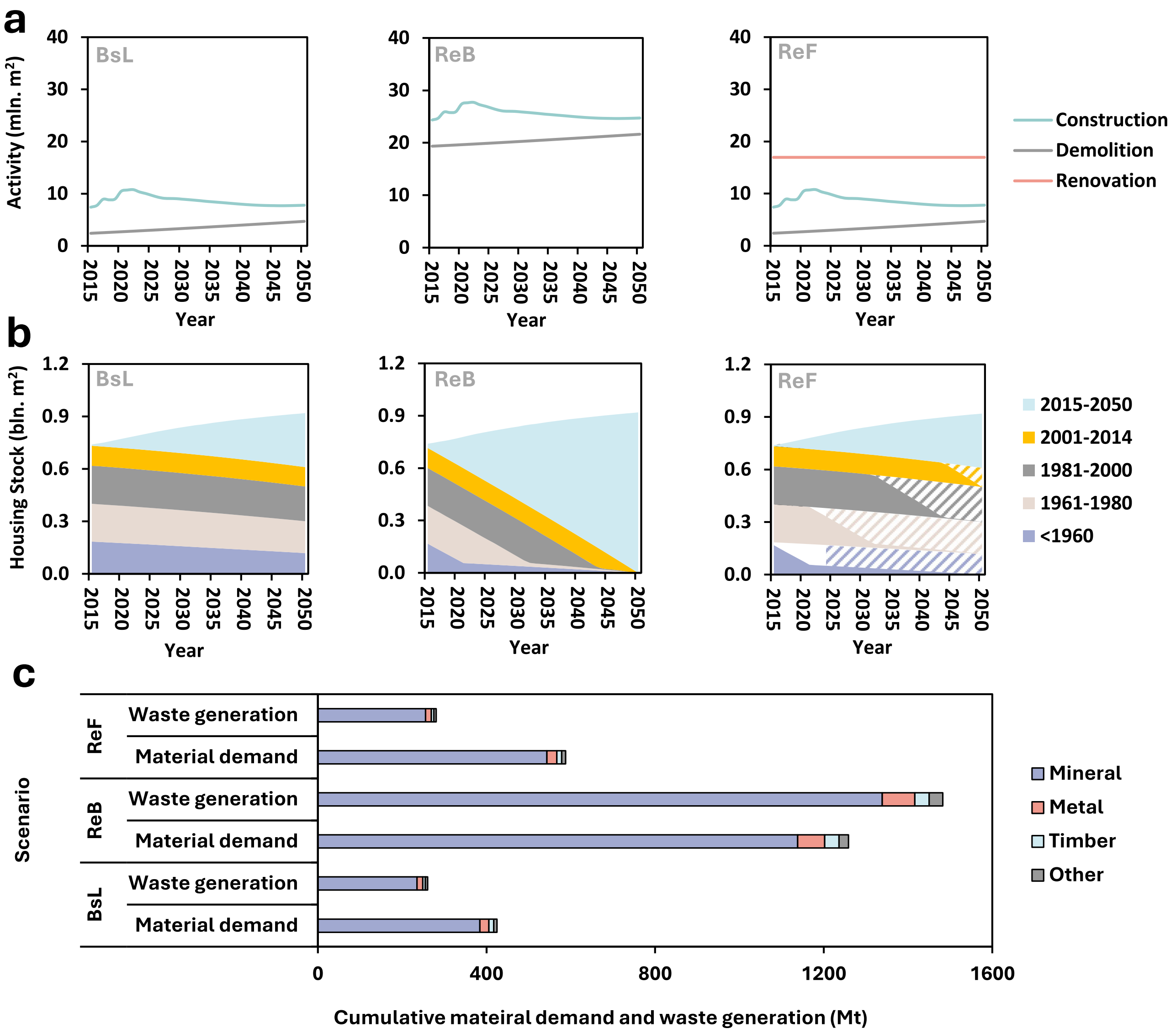

Fig. 1 | Housing activities, stocks, and material demand and waste generation under three scenarios for 2015–2050. **a** Annual construction, demolition, and renovation activities in three scenarios. **b** Annual housing stocks across three scenarios. The strip-patterned areas represent refurbished housing stocks. **c** Cumulative material demand and waste generation in three scenarios between 2015 and 2050. It is noted that the material demand in this figure indicates direct material usage as opposed to material footprint.

CDW, reaching 54–58%, 1%, and 5–6%, respectively, with a concurrent reduction in the downcycling rate to 32–37%.

Carbon, material, and economic footprints

Under the 3.5 °C pathway, three scenarios exhibit a consistent trend: a decline in GHG emissions by 2035 and an increase after that (Fig. 3a). This is due to anticipated increased coal use in power generation from 2035 to 2045 to meet growing energy demand in Europe under the 3.5 °C pathway[42]. The ReB 3.5 °C HR and ReF 3.5 °C HR scenarios exhibit higher carbon footprints in 2015—each at 29 Mt CO_2-eq—compared to 26 Mt CO_2-eq in the BsL scenario. The carbon footprint of the BsL 3.5 °C HR scenario exceeds that of the ReB 3.5 °C HR and ReF 3.5 °C HR scenarios in 2026 and 2033. Under the 1.5 °C pathway, all scenarios demonstrate a substantial reduction in carbon footprints compared to the 3.5 °C pathway. Starting from 26 to 28 Mt CO_2-eq in 2022, carbon footprints of the BsL, ReB, and ReF scenarios sharply decrease, reaching 13 Mt CO_2-eq, 4–7 Mt CO_2-eq, and 12 Mt CO_2-eq, respectively, by 2050.

Figure 3b presents the cumulative carbon footprint disaggregated by life cycle stage. Among all scenarios, the ReF 3.5 °C HR scenario exhibits the highest net cumulative emissions at ~966 Mt CO_2-eq, whereas ReB 1.5 °C EC achieves the lowest at 582 Mt CO_2-eq. It is found that façade refurbishment offers limited climate benefits due to its substantial upfront embodied emissions. Consequently, the ReF scenario only delivers marginal improvements over the BsL scenario, with variations ranging from −0.3% to +1.3%, depending on the context. Decarbonisation is more sensitive to energy transition pathways than renovation strategies. While the most ambitious renovation scenario (ReB 1.5 °C EC) yields a cumulative mitigation up to 119 Mt CO_2-eq—representing a 17% reduction compared to BsL reference—adopting a 1.5 °C energy transition delivers greater benefits, with reductions ranging from 239 to 304 Mt CO_2-eq, or a 25–33% compared to the corresponding 3.5 °C scenarios.

The predominant portion of the cumulative carbon footprint stems from home operation, accounting for ~430–853 Mt CO_2-eq, constituting 69–91% of the total cumulative carbon footprint across all scenarios. The GHG emissions from home construction in the BsL and ReF scenarios range between 110 and 128 Mt CO_2-eq, representing 13–16% of the cumulative carbon footprint. The substantially higher construction carbon footprint in the ReB scenario is particularly noteworthy, estimated at around 323–380 Mt CO_2-eq. In the ReF

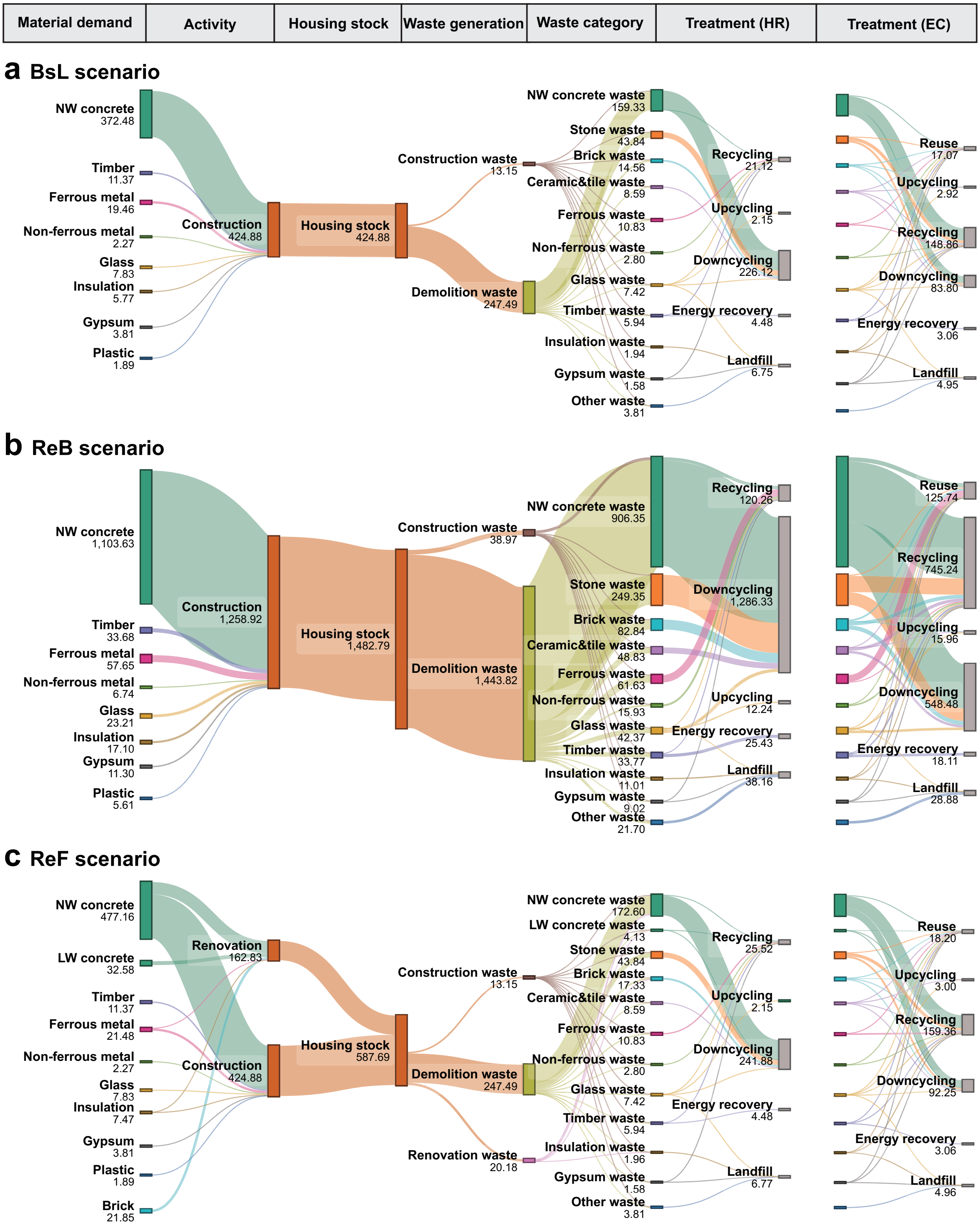

Fig. 2 | Cumulative material demand and waste management (unit: Megatonne, Mt) between 2015 and 2050 under three scenarios. a Cumulative material demand and waste management in the Baseline (BsL) scenario. **b** Cumulative material demand and waste management in the Rebuild (ReB) scenario. **c** Cumulative material demand and waste management in the Refurbishment (ReF) scenario. HR High Recovery strategy, EC Enhanced Circularity strategy, NW concrete normal-weight concrete, and LW concrete light-weight concrete. It is noted that the material demand in this figure indicates direct material usage as opposed to material footprint.

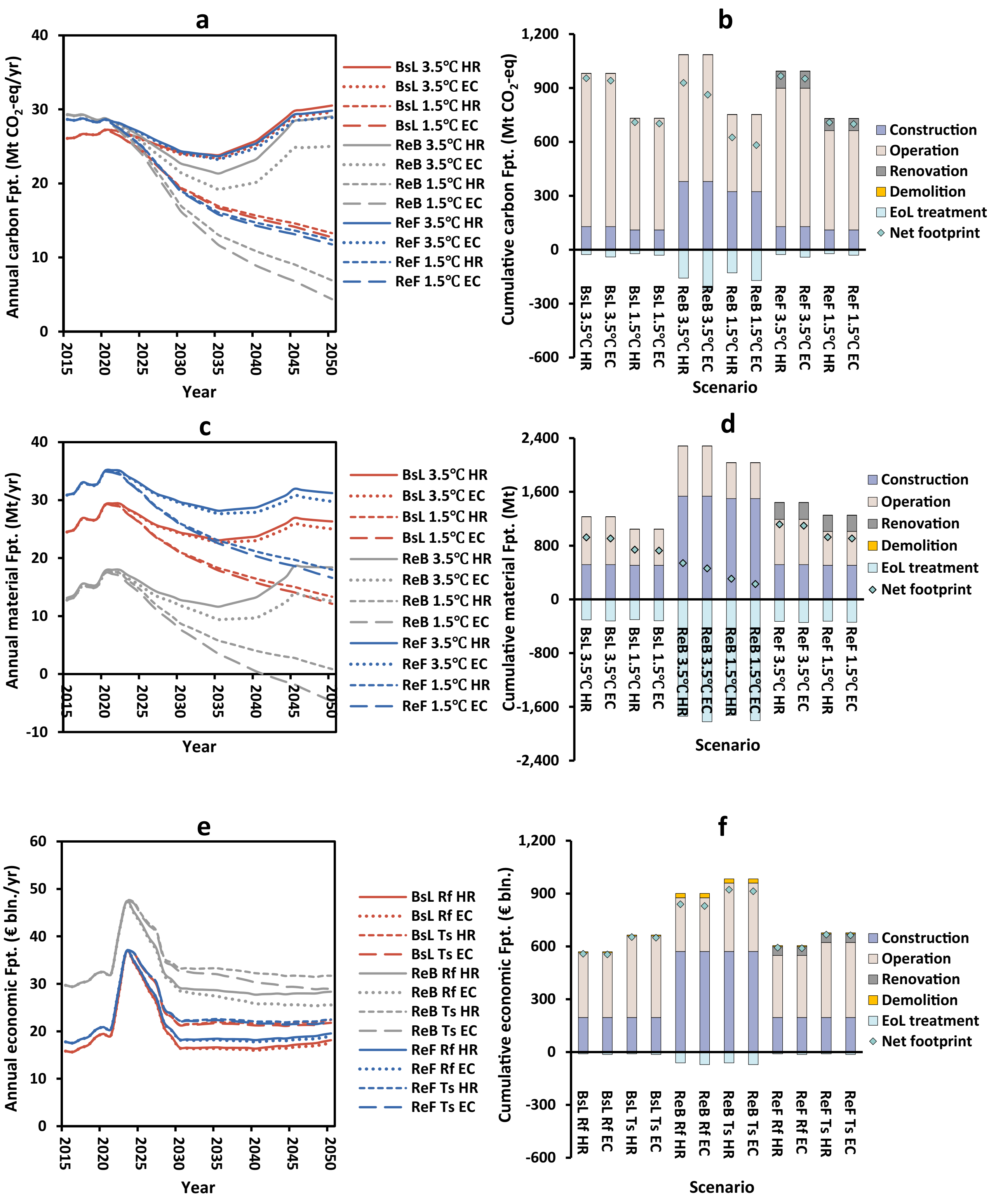

Fig. 3 | Comparison of annual and cumulative carbon, material, and economic footprints of the Dutch residential sector for the period 2015–2050 across different energy renovation scenarios and socioeconomic contexts. **a** Annual carbon footprint. **b** Cumulative carbon footprint. **c** Annual material footprint. **d** Cumulative material footprint. **e** Annual economic footprint. **f** Cumulative economic footprint (interest rates are applied to convert annual value to net present value for 2020). It is noted that building operation includes the energy use and associated costs of household heating and cooling, cooking, domestic hot water supply, electrical appliances, and lighting. BsL Baseline scenario, ReB Rebuild scenario, ReF Refurbishment scenario, 3.5 °C IMAGE SSP2-RCP6 pathway, 1.5°C IMAGE SSP2-RCP19 pathway, HR High Recovery strategy, EC Enhanced Circularity strategy, Rf Europe-Russia Relief, and Ts Europe-Russia Tensions. A detailed summary of annual footprints is provided in Supplementary Fig. 12 in the Supplementary Information.

scenario, the cumulative GHG emissions from renovation activities amount to 68–95 Mt CO_2-eq, which makes up 10% of the overall carbon footprint. Despite constituting a minor fraction of the total emissions, it still contrasts with those resulting from demolition, which is less than 0.1% across all scenarios.

While the benefits of material circulation strategies on GHG mitigation are minimal within the BsL and ReF scenarios, their importance is notably amplified in the ReB scenario, primarily due to the substantial increase in recoverable CDW from home rebuilding. In the ReB scenario, a cumulative reduction of 124–158 Mt CO_2-eq emissions is expected following the current waste management practice. Adopting advanced circularity technologies could lead to an additional 66 Mt CO_2-eq reduction in the ReB 3.5 °C EC scenario and 43 Mt-CO_2-eq in the ReB 1.5 °C EC scenario compared to HR-based scenarios.

Figure 3c, d further compares the annual and cumulative material footprints across all scenarios. Under a moderate energy transition, as depicted under the 3.5 °C pathway, the material footprints of the BsL, ReB, and ReF scenarios exhibit a declining trend post-2020, followed by an ascent from 2035 to 2045 (Fig. 3c). This is attributed to increased coal use for power generation, mirroring the trajectory of the carbon footprint. However, under the 1.5 °C pathway, three energy renovation scenarios show a monotonous decline after 2020. In particular, the material footprint of the ReB 1.5 °C EC scenario is expected to reach net zero around 2041. In 2050, a reduction in material footprint by 13–17 Mt could be attained in the 1.5 °C pathway compared to the 3.5 °C pathway, depending on scenarios. The per-annum material footprint of the ReF scenario is 4–6 Mt higher than that of the BsL scenario concerning each material circulation strategy and energy transition pathway for the period 2020–2050, while the ReB scenario shows a noticeable reduction of 8–17 Mt over that period. Moreover, it is observed that the disparity between the HR and EC strategies is almost inconsequential in terms of material footprint, regardless of the energy renovation scenarios and energy transition pathways.

Figure 3d shows that the ReB scenario has a considerably larger material footprint from home rebuilding, while material circulation could also offset the material footprint. The ReF scenario exhibits the highest net material footprint, compared to the ReB and BsL scenarios. In contrast to the carbon footprint, the construction stage holds equal importance to the operation stage regarding the cumulative material footprint from 2015 to 2050 in the BsL and ReF scenarios. This corresponds to 507–518 Mt of a cumulative material footprint from home construction in these two scenarios, accounting for 36–49% of the overall material footprint when the EoL stage is excluded. The material footprint of home construction is even more noticeable in the ReB scenario, reaching 1501–1536 Mt and comprising 67–74% of the overall material footprint when excluding the EoL stage.

The impact of the energy transition on material footprint reduction is almost negligible for the construction, renovation and EoL stages. In contrast, transitioning to the 1.5 °C pathway, the cumulative material footprint from the operation stage could be reduced by 167–214 Mt between 2015 and 2050, depending on scenarios, representing 24–29% of the operational material footprint reduction. This is attributed to the savings of fossil fuel materials that would have been used as energy sources. While fossil fuel materials used in manufacturing and recovery processes may also decrease, construction bulk materials—accounting for the largest share of the material footprint and essential for structural purposes—remain largely unaffected.

Interestingly, while its contribution to decarbonisation may not be prominent, the circular economy plays a vital role in reducing the material footprint of energy renovation. Around 25–31% of the cumulative material footprint could be offset in the BsL scenario by recovering CDW to displace primary materials, 23–27% in the ReF scenario, and 76–89% in the ReB scenario.

In contrast to the fluctuations observed in carbon and material footprints, the economic footprint remains relatively stable, except from 2022 to 2030, when the energy market in Europe is still under the influence of the Russo-Ukrainian War. Since the outbreak of the war in 2022, it is anticipated that power prices in the Netherlands would experience a surge, reaching a peak in 2024 and stabilising around 2030. As a result, it is seen from Fig. 3e that the economic footprint in the BsL and ReF scenarios is projected to double (around €34–37 billion) in 2024, followed by stabilisation at ~€21–23 billion under the Ts trend and €16–20 billion following the Rf trend from 2030 onwards. The economic footprint of the ReB scenario increases from €32 billion in 2021 to up to €47 billion in 2023 and then fluctuates between €25–33 billion after 2030. Suppose the relation between Europe and Russia continues to intensify, it is anticipated that the household energy utility would experience a rise ranging from €2–5 billion per annum from 2022 to 2050. This would result in a cumulative total cost between 2015 and 2050 of €73–95 billion, calculated as the net present value of the year 2020. Hereafter, all cumulative cost references are presented as net present values.

Due to additional expenses associated with façade refurbishment, the overall cumulative economic footprint of the ReF scenario is slightly higher than in the BsL scenario, with an increase ranging from 2% to 6% (Fig. 3f). The economic benefits of CDW recovery in both BsL and ReF scenarios are comparable, amounting to €10–14 billion. The proceeds in the ReB scenario are much higher than those from these scenarios, ~€62–71 billion. The ReB scenario exhibits the highest net cumulative economic footprint, ranging from €830–922 billion. This is primarily attributed to the construction costs of €571 billion, approximately two times higher than those in the BsL and ReF scenarios.

Critical housing stocks and waste streams

The carbon footprint results emphasise the pivotal role of energy transition in energy renovation, as it reduces emissions across all building life cycle stages, particularly the operation stage. Under the 1.5 °C pathway, the carbon footprint associated with construction, renovation, and demolition per square metre of home in 2050 could be reduced by 31–53% compared to the 2015 levels (Fig. 4a). Even more substantial reductions are observed in the operation stage, with average carbon footprints dropping by 60–67% in the BsL and ReF scenarios (from 31–32 kg CO_2-eq/m^2 to 10–13 kg CO_2-eq/m^2) and by 91% in the ReB scenario (from 31 kg CO_2-eq/m^2 to 3 kg CO_2-eq/m^2).

Refurbishing the façades of older homes offers greater potential for mitigating operational emissions (Fig. 4b). For instance, refurbishing homes built before 1960 reduces per-m^2 carbon footprint by 33%, from 39 kg CO_2-eq/m^2 to 26 kg CO_2-eq/m^2 in 2015, whereas refurbishing homes built between 2001 and 2014 achieves only a 7% reduction. With the energy transition gaining momentum over time, these disparities would enlarge slightly by 2050, with reductions of 38% and 8%, respectively. Figure 4c shows that, in the ReB scenario, ~43–51% of the cumulative operational emission reduction is achieved by rebuilding homes constructed before 1960. Similarly, in the ReF scenario, refurbishing homes built before 1960 contributes to an even higher share, accounting for 61–63% of the total emission reduction. However, such a reduction in rebuilding and refurbishing homes built between 2001 and 2014 is negligible. This indicates that prioritising energy renovation for the worst-performing buildings offers the highest climate benefits.

Figure 4d–f provides a detailed breakdown of the cumulative carbon, material, and economic footprints from the EoL treatment stage based on the material categories. As shown in Fig. 4d, ~56–82% of the carbon footprint reduction is from metal recycling. However, the climate benefits from metals recycling have peaked, as metals are already recycled at nearly 100% in the Netherlands. Further efforts to increase the reuse of metal components yield only an additional 4–5% reduction in carbon footprint. Yet, advancing waste management for mineral wastes could lead to 2–3 times more carbon reduction than their current practices.

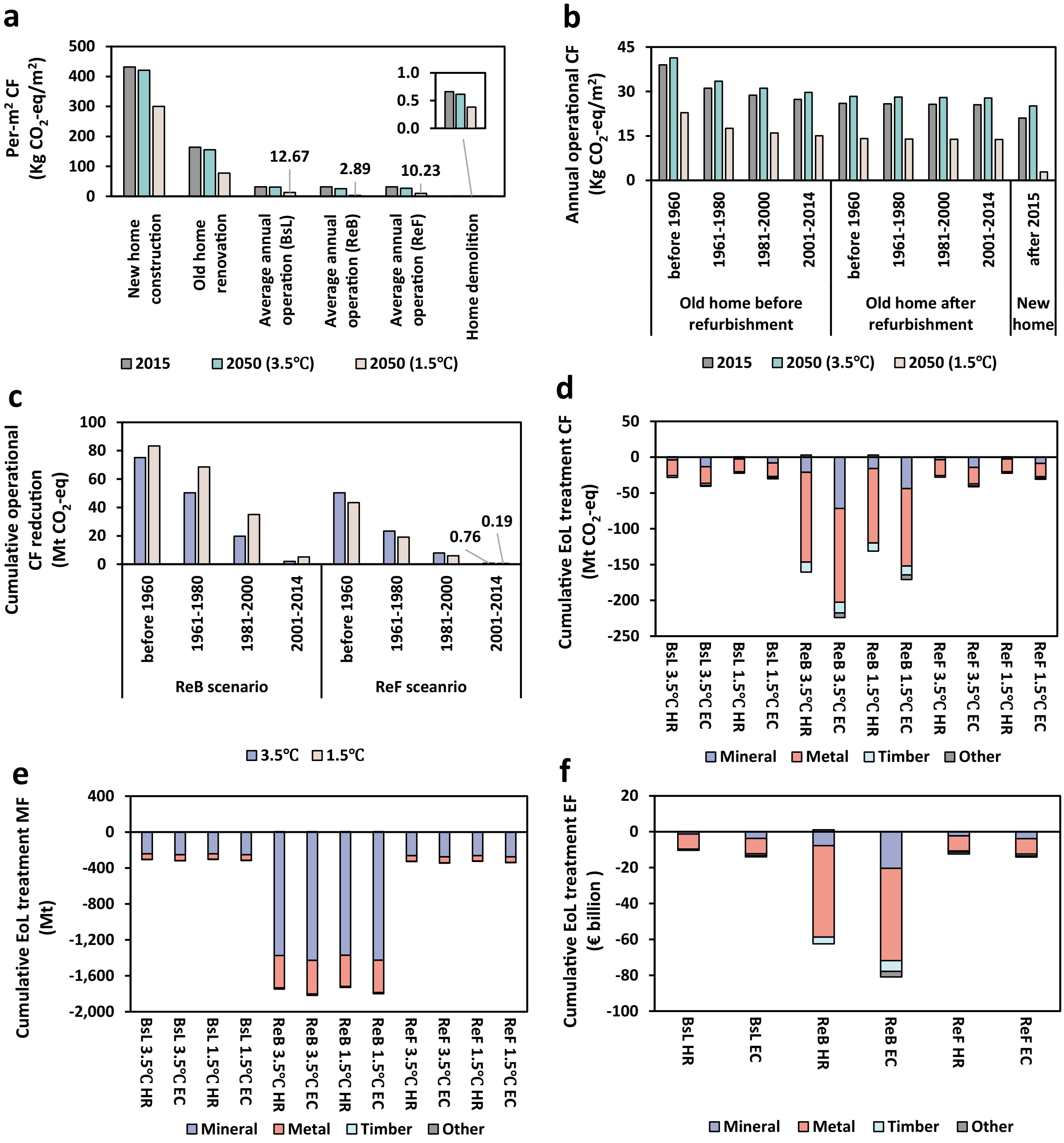

Fig. 4 | Breakdown of footprints based on construction cohorts and material categories. a Carbon footprint (CF) of per-m² construction, renovation, annual operation, and demolition. **b** Annual per-m² operational CF of homes constructed in different cohorts. **c** Cumulative operational CF (between 2015 and 2050) of homes constructed in different cohorts. **d** Cumulative CF from the end-of-life (EoL) treatment stage. **e** Cumulative material footprint (MF) from the EoL treatment stage. **f** Cumulative economic footprint (EF) from the EoL treatment stage. It is noted that building operation includes the energy use and associated costs of household heating and cooling, cooking, domestic hot water supply, electrical appliances, and lighting.

This pattern extends to the economic footprint as well. Under the current waste management system, metals account for 61–83% of the value in waste recovery; however, transitioning to an advanced material circulation system would provide only a modest 1% increase in economic gains for metals (Fig. 4f). In contrast, implementing high-value-added recovery routes for mineral wastes could boost revenues from mineral waste management by up to approximately two times. Moreover, Fig. 4e highlights that minerals, rather than metals, predominantly contribute to reducing the material footprint in waste recovery, with a share of 79–81%. This further underscores the untapped potential in mineral waste recovery systems.

Sensitivity analysis for household heating decarbonisation

Given the importance of household heating transition for residential decarbonisation, sensitivity analyses are performed to evaluate the impact of alternative insulation materials, refurbishment approaches, and heating technology mixes on operational carbon emissions.

Insulation materials play a crucial role in building energy renovation. Both types of PCEs used in this study incorporate an advanced thermal material—aerogel—to improve the thermal performance of existing and new homes. However, aerogel is still produced at a lab scale within the VEEP project[43], resulting in higher carbon, material, and economic footprints during production than conventional materials such as expanded polystyrene (EPS). To assess these trade-offs, we compared the aerogel-based PCEs with an EPS-based alternative. A detailed introduction to the alternative PCEs is provided in Supplementary Fig. 6 and Supplementary Tables 24–26 in the Supplementary Information (SI). Results show comprehensive benefits (Supplementary Fig. 7, SI): a 2–6% reduction in cumulative lifecycle carbon footprint and 1–3% in economic footprint, depending on the scenario. Material savings are more pronounced in resource-intensive scenarios —2% in BsL, 5–6% in ReF, and 11–23% in ReB. This highlights the need to evaluate insulation materials holistically, considering both operational and embodied impacts. Future renovation strategies should actively screen and prioritise scalable, cost-effective, and low-carbon insulation materials to support environmental and economic sustainability goals.

Refurbishing existing homes may target either façade insulation or heating systems. As the VEEP project focuses on PCE-based façade cladding, heating system replacement was excluded from the main analysis due to missing inventory data. To address this gap, a sensitivity analysis was conducted using a new scenario—heating system refurbishment—in which traditional heating systems in all existing homes are replaced with electric heat pumps, hybrid heat pumps, district heating, or biogas boilers, in proportions matching those installed in new homes. Results (see Supplementary Fig. 8, SI) show that heating system upgrades reduce the cumulative operational carbon footprint to 729 Mt CO_2-eq under the 3.5 °C pathway and 488 Mt CO_2-eq under the 1.5 °C pathway—representing a reduction of 15% and 22% compared to the BsL scenario, and 5% and 11% to the original ReF scenario. Although less impactful than full-scale rebuilding, this approach noticeably outperforms façade cladding. However, practical challenges such as occupant disruption, unquantified embodied emissions and financial costs, remain outside the scope of this sensitivity analysis.

Heating technology mixes could also affect operational emissions in energy renovation. This study adopts the High Heat Pump scenario from Verhagen et al.[29], which anticipates a growing share of electric heat pumps in the Dutch residential heating market. To test the robustness of our findings, two alternative heating scenarios from the same study are introduced—one favouring low-temperature district heating and electric heat pumps, and the other with a higher share of hybrid heat pumps—across both the 3.5 °C and 1.5 °C pathways (Supplementary Fig. 9, SI). Results show that choices in heating technology mixes have a marginal effect on operational carbon footprints, with variations between −0.7% and +1.2%, as shown in Supplementary Fig. 10 in the SI. This implies that grid decarbonisation and clean energy supply matter more than the choice of gas-free heating hardware under identical transition pathways.

These findings emphasise the importance of adopting a systems-level approach when planning heating renovations. While advanced insulation and efficient heating systems could yield meaningful operational carbon savings, their benefits must be balanced against embodied impacts, economic feasibility, and user acceptance. Together, these insights suggest that future renovation policies and technologies should prioritise low-embodied-carbon materials, scalable interventions, and alignment with national energy transition goals to ensure effective and sustainable decarbonisation of residential heating.

Discussion

Based on the findings, this section discusses the trade-offs and synergies in building energy renovation, its policy implications for Europe, and the study's limitations and future outlook. Clear trade-offs can be observed in different scenarios for building energy renovations. In the ReF scenario, building façade refurbishment is an effective means for decarbonising home operations, while resulting in more embodied GHG emissions from the renovation stage. Refurbishment also leads to higher lifecycle costs and more material use. Such trade-offs become more remarkable in the context of substantial rebuilding. The ReB scenario could mitigate greater operational GHG emissions, whereas it nearly triples the cumulative GHG emissions, material use, and expenses during construction.

A circular economy could facilitate such a low-carbon transition with more material-efficient solutions. At the same time, its contributions to decarbonisation and cost-effectiveness remain modest in the context of building energy renovation. Shifting to a high-value-added CDW management system could further reduce material use at the waste treatment stage by 5–6% and lower costs by 15–38%, depending on scenarios. Its impact is more noticeable in terms of carbon footprint reduction, with an additional decrease of 33–51% anticipated at the waste treatment stage. However, the additional climate benefits from adopting advanced CDW management strategies become almost negligible when considering the entire life cycle of the building.

The clean energy transition is the cornerstone of decarbonising the built environment, exerting a transformative impact far exceeding the contributions of building renovation and circularity strategies. Energy transition also plays an essential role in reducing the material used at the operation stage, primarily by phasing out fossil fuel-based materials such as coal for energy production. However, its influence on the construction, renovation, and EoL stages remains limited, as the material footprint in these stages is predominantly driven by construction materials like sand and gravel, which are challenging to dematerialise through the energy transition.

Ensuring the economic viability of circularity and low-carbon strategies in building energy renovation is vital for enabling their widespread implementation. The Dutch CDW management sector is expected to generate net economic benefits. Yet, this is based on the ideal condition that the produced secondary raw materials could fully replace virgin materials on a 1:1 basis. In reality, the effectiveness of this replacement is often limited by factors such as material quality, processing costs, and market demand, which may reduce the actual economic gains or reverse the profitability. On the other hand, the potential cost savings from reduced energy use are insufficient to offset the expenses associated with refurbishment and rebuilding. Moreover, the volatility of power prices caused by the Russo-Ukrainian War noticeably influences the cost-effectiveness of household energy utilisation in the Netherlands, adding a layer of uncertainty to long-term investment planning.

In conclusion, the findings indicate that radical renovation strategies, such as rebuilding, have the potential to achieve deep decarbonisation when underpinned by an ambitious energy transition. However, this progress comes with a substantial increase in material consumption and costs. While circular economy strategies could remarkably help mitigate material usage, a rise in capital costs remains inevitable. Furthermore, the remaining global carbon budget is already insufficient to accommodate both operational and embodied emissions, making large-scale rebuilding particularly challenging due to its high upfront carbon emissions, as seen in Switzerland[44]. We provide an additional assessment of the extent to which the Dutch residential sector could achieve the circularity and decarbonisation goals in Section 7 of the SI. It shows that the ReB 1.5°C EC realises an 83% carbon reduction—close, but still short of the 94% 2050 target (see Supplementary Fig. 11 and Supplementary Table 27, SI). This highlights the need for low-embodied-carbon solutions such as advanced recycling, bio-based materials, or a reallocation of the carbon budget to make rebuilding compatible with long-term climate goals.

Under a broader context, the interaction between a circular economy and a low-carbon economy is one of opposition and unity. Their distinctions could be clarified through a more concise explanation of the relation between material and energy. A circular economy emphasises preventing and circulating bulk materials to construct artificial components and structures[45]. In contrast, a low-carbon economy prioritises replacing fossil fuel materials primarily used for power generation[45]. Despite their differences, these two economic modes are also correlated—material circulation mitigates the embodied GHG emissions[46], while renewable energy sources facilitate material circulation[45]. Moreover, the economic viability of these two modes faces challenges—recovery is not consistently profitable and low-carbon technologies entail high upfront costs. Therefore, holistic strategies are needed to simultaneously address the intertwined challenges in Europe's built environment.

The EU faces similar challenges in its built environment, with a high CDW recovery rate and ageing building stocks. Given the similarities between Europe and the Netherlands (as detailed in Supplementary Section 5.1 of the SI), this study explores policy recommendations to advance sustainable energy renovations across the broader European context. Key strategies include adopting life cycle thinking, aligning renovation with energy transition progress, enhancing circular renovation practices, and strengthening economic incentives to accelerate large-scale implementation. These recommendations are elaborated in the following paragraphs.

Energy renovation is more than a series of isolated upgrades—it is a complex system engineering that involves different life cycle stages, including material production and transport, construction, operation and maintenance, renovation, demolition, and waste treatment. Although prioritising the renovation of older buildings yields greater marginal benefits, the decision to tear them down or refurbish them requires a comprehensive evaluation of all relevant factors. Additionally, while the operation stage contributes the most to a building's life cycle GHG emissions, focusing solely on operational emissions could lead to a trade-off that reduces impacts in one stage but increases them in others. Therefore, life cycle thinking is essential to ensure that efforts in one area do not create unintended negative consequences elsewhere, ultimately leading to more sustainable and efficient outcomes[47]. Further policy implications on this are described in Supplementary Section 5.2 of the SI.

In the EU, space heating accounts for ~64% of final energy usage in households, while cooling remains minimal at just 0.6% of the total[48]. This stark imbalance highlights the need to focus energy renovation efforts on enhancing the insulation performance of building envelopes and replacing traditional heating systems with high-efficiency alternatives. Our findings indicate that energy transition plays a more fundamental role than renovation in achieving decarbonisation. Initiating renovation prematurely, without the simultaneous development and deployment of clean energy sources, risks squandering resources and investments. Therefore, the energy transition, particularly in heating system renovation, must be closely aligned with the local renewable energy plans to ensure both decarbonisation and efficiency. By tailoring heating solutions to the available local resources—whether through renewable district heating, heat pumps powered by wind electricity, or the integration of biogas-based boilers—the heating sector could substantially contribute to decarbonising the built environment. This alignment supports the EU's climate goals and ensures that heating systems are cost-effective, energy-efficient, and resilient to future energy challenges. Detailed policy background for this can be found in Supplementary Section 5.3 of the SI.

Circular renovation should be promoted as a standard practice during the building energy renovation[49]. To boost the circularity in energy renovation, it is necessary to implement waste audits, selective demolition, prefabrication, advancing CDW treatment technologies, and setting quantifiable circularity goals. First, mandatory pre-demolition and pre-renovation waste audits are essential to assess the types and quantities of construction products and materials that would be deconstructed or demolished and to provide recommendations for their subsequent management[50]. This process helps identify and locate hazardous substances, while also creating a comprehensive inventory of building components and materials that can be reused and recycled. Then, selective demolition is also imperative to guarantee the effective sorting and separation of each fraction of CDW in quality, thereby assuring a higher circularity potential[51]. Additionally, prefabricated components, such as the PCEs in this study, which are increasingly used in building renovation, require thorough waste audits and careful disassembly to ensure that materials are properly handled for reuse and recycling. Moreover, upgrading the current CDW management system could strengthen closed-loop recovery practices, making the European recycling industry more resilient and competitive in response to market fluctuations. Finally, quantitative benchmarks provide clear objectives, enabling stakeholders to measure progress, identify gaps, and implement strategies to close the material loop effectively. Detailed policy background for this can be found in Supplementary Section 5.4 of the SI.

Several key actors are involved in energy renovation, with the core stakeholders being the government and homeowners. Government involvement is essential as it provides the necessary leadership, initiation, direction, support, and even mandatory regulations to drive the circular and low-carbon transition of the built environment. Despite government efforts, energy renovation in the private residential sector ultimately depends on individual homeowners' decisions. Homeowners always weigh the anticipated benefits against the costs to determine whether to proceed, a consideration made even more critical amidst the global economic recession. However, the potential cost savings resulting from reduced energy use fail to offset the expenses of renovation and rebuilding, deterring them from readily embracing renovation initiatives. Therefore, a participatory and neighbourhood-oriented approach with comprehensive economic incentivising measures is essential to ensure the successful implementation of energy renovations[52]. Detailed policy background and measures are discussed in Supplementary Section 5.5 of the SI.

Given the complexity of building energy renovation as a system engineering challenge, this study applied several simplifications to manage its intricacy in modelling. These include simplifications in the scope of renovation options and techniques, housing stock and material flow modelling, energy prices and interest rates, and truncation errors in life cycle inventory modelling[53–55]. Details of these limitations are elaborated in Supplementary Section 6 of the SI. Although this study offers a simplified reflection of reality, the assessment still yields insights into the trade-offs and synergies between the circular and low-carbon economies and their economic viability in building energy renovation. Based on those limitations, our future work aims to expand on this field by exploring a more comprehensive range of scenarios and regions with more harmonised and comprehensive methods.

Methods

Overview of methods

This study investigates the interplay between decarbonisation, circularity, and cost-effectiveness in building energy renovation for the Dutch residential sector from 2015 to 2050. An integrated regional footprint analysis model is developed by combining a dynamic material flow analysis (dMFA) with a lifecycle-based footprint analysis, as shown in Fig. 5. The decarbonisation and circularity levels are measured by carbon (in kg CO_2-eq) and material (in kg of Total Material Requirement) footprints, respectively, using life cycle assessment (LCA). The cost-effectiveness is quantified with economic footprint[56] (in €) using life cycle costing (LCC). The application of LCC to assess the regional economic footprint is further elaborated in Section Footprint assessment. The outcome of the dMFA module is used as size factors, enabling the scaling up of unitary carbon, material, and

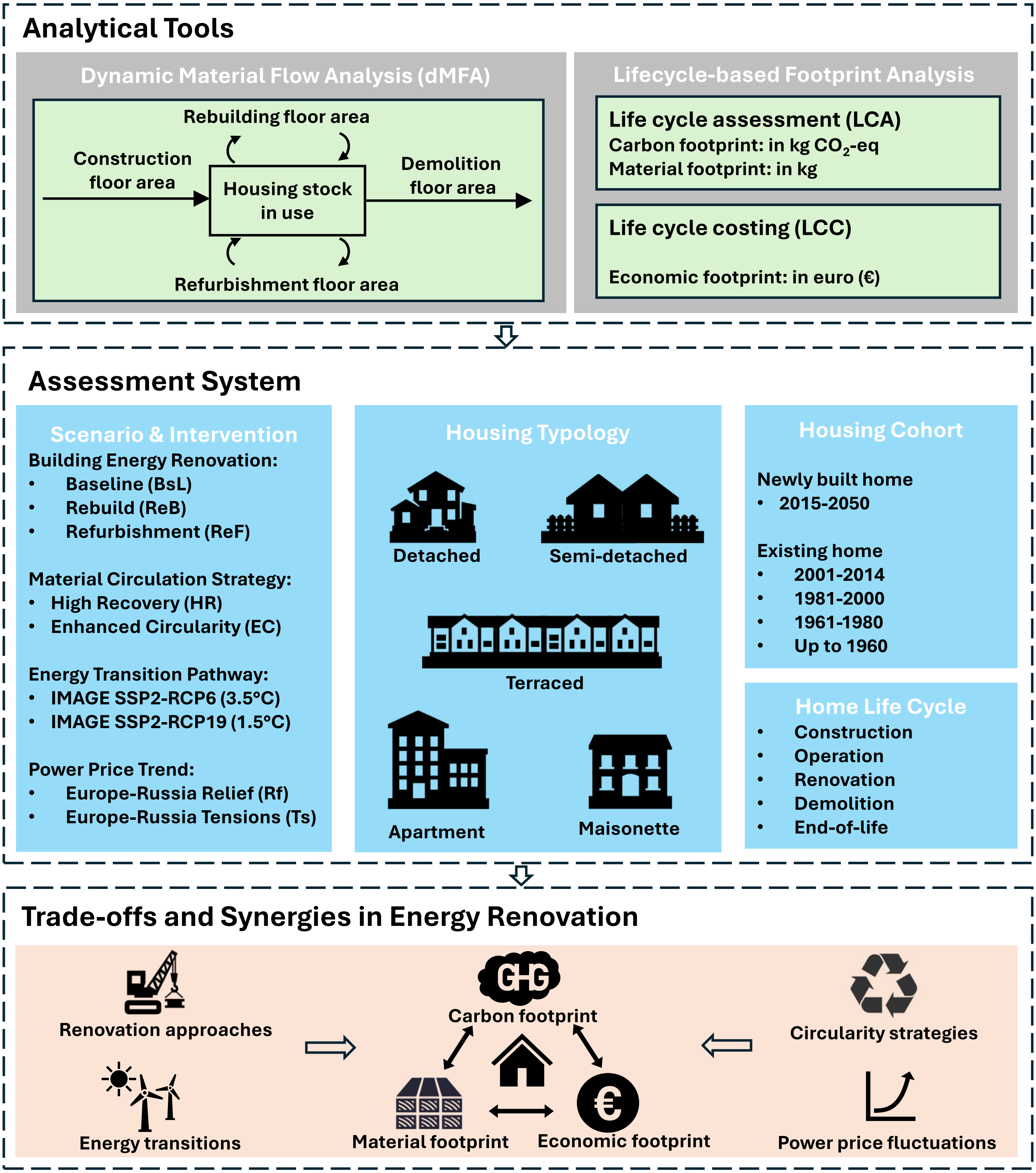

Fig. 5 | Methodological framework of this study.

economic footprints to a national level. Three renovation scenarios are defined: Baseline (BsL), Rebuild (ReB), and Refurbishment (ReF). These are analysed within three superimposed socioeconomic and political contexts: Material Circulation Strategies, Energy Transition Pathways, and Power Price Trends. Five types of homes are considered under five vintage cohorts. The assessment scope encompasses activities related to building construction, operation, renovation, demolition, and waste treatment, with the consideration of the transport of materials and wastes. Based on our research findings, we present interpretations of trade-offs and synergies in building energy renovation and discuss relevant policy implications in the broader European context.

Scenario and intervention narratives

Three scenarios are developed to examine various strategies for building energy renovation: a BsL scenario with no additional renovation effort aimed at achieving energy neutrality, a ReB scenario involving the demolition and reconstruction of energy-inefficient homes that were built before 2015, and a ReF scenario focused on the utilisation of recently developed prefabricated concrete elements (PCEs)[57,58] that incorporate high-insulating materials to refurbish the façade of existing housing stock built before 2015. In the three scenarios, the newly constructed homes exhibit superior thermal insulation performance and would progressively transition to gas-free

Table 1 | Description of scenarios and interventions

Scenarios and interventions	Description	Affected footprint category
Building renovation scenarios	Baseline (BsL): with no additional renovation effort Rebuild (ReB): demolishing and rebuilding houses built before 2015 Refurbishment (ReF): refurbishing the façade of houses built before 2015 using the prefabricated concrete element system[41]	Carbon footprint Material footprint Economic footprint
Material circulation strategies	High Recovery (HR): sustaining the ongoing downcycling routes for CDW treatment till 2050[34,60] Enhanced Circularity (EC): maximising recycling, upcycling, and reuse for CDW treatment by 2050[68]	Carbon footprint Material footprint Economic footprint
Energy transition pathways	IMAGE SSP2-RCP6 (3.5 °C): continuing with a moderate energy transition to curb the global temperature increase to 3.5 °C by 2100 related to pre-industrial levels[42] IMAGE SSP2-RCP19 (1.5 °C): embracing an ambitious energy transition to restrain the global temperature rise to 1.5 °C by 2100 related to pre-industrial levels[42]	Carbon footprint Material footprint Economic footprint
Power price trends	Europe-Russia Relief (Rf): the easing of tensions in the relationship between Europe and Russia is expected[67], resulting in a stabilisation of power prices in the Netherlands Europe-Russia Tensions (Ts): the current tensions between Europe and Russia are expected to persist[67], increasing power prices in the Netherlands	Economic footprint (operational only)

systems for heating, cooking, and hot water supply. Specifically, a different type of PCE is used in the construction of exterior walls of these new homes across all scenarios[59]. In the meantime, the homes built pre-2015 continue to rely primarily on natural gas-based heating systems, while homes constructed after 2015 would progressively transition to using electricity and bioenergy-based heating systems.

Two material circulation strategies, High Recovery (HR) and Enhanced Circularity (EC), were established for the EoL treatment of CDW. The High Recovery (HR) strategic route assumed that the Netherlands would continue with the existing technological routes for CDW treatment. This implies that the Dutch building sector would persistently maintain a high recovery rate, primarily through downcycling. The status quo of CDW management is collected from the literature[34,60] and national waste statistics of the Netherlands[61]. The EU[15] and the Netherlands government[62] are striving to reap the full potential of CDW by promoting preparation for reuse and high-quality recycling. Therefore, the Enhanced Circularity (EC) strategy prioritises shifting away from downcycling to more favourable operations within the waste hierarchy, such as recycling, upcycling, and preparation for reuse[51]. The assumptions and references for managing each CDW stream from 2015 to 2050 in both strategic routes are detailed in Supplementary Section 1.5.2 in the Supplementary Information (SI).

Energy transition pathways involve different levels of renewable energy penetration to facilitate decarbonisation in the residential sector. Pathways presented in this study are based on prospective narratives from the Integrated Assessment Model (IAM) IMAGE 3.2[42]. In that model, multiple distinctive socioeconomic transition scenarios were crafted by coupling the Shared Socioeconomic Pathways (SSPs)[63] and Representative Concentration Pathways (RCPs)[64]. We use the SSP2—'middle-of-the-road' pathway—that foresees a moderate population and GDP growth consistent with the historical trajectory[63]. Specifically, the IMAGE SSP2-RCP6 and IMAGE SSP2-RCP19 pathways have been delineated, each with the explicit goal of restraining the global temperature rise to 3.5 °C and 1.5 °C, respectively, by the end of this century in comparison to pre-industrial levels. Compared to the baseline 3.5 °C pathway, the more ambitious 1.5 °C pathway entails a higher share of renewable and low-carbon energy sources (e.g., solar, wind, and biomass) in energy systems alongside the deployment of carbon capture and storage (CCS) technologies for the production and supply of construction materials, household energy, and demolition and CDW treatment services. A Python-based package, Premise v2.0.2[65], incorporates the IAM scenarios into the life cycle inventory database ecoinvent 3.9 Allocation, Cut-off by Classification[66].

Russia's military aggression against Ukraine has caused substantial disruptions to the European energy system, causing increased energy prices and heightened energy security risks[32]. Given the profound changes in the European energy market resulting from the war, Energy Brainpool presents multiple scenarios to project European power price fluctuations. These scenarios are driven by the Russo-Ukrainian War and the evolving relationship between Russia and Europe, which subsequently affects Europe's decisions to import gas, oil, and coal from Russia[67]. The distinctions pertain to the assumptions in each scenario regarding the trends of commodity prices and energy demand. Two extreme trends, Europe-Russia Relief (Rf) and Europe-Russia Tensions (Ts), are selected to model the energy utility cost of Dutch households[67]. The Rf trend envisions a gradual easing of relations between Europe and Russia in the coming years, resulting in the resumption of Russian pipeline gas imports in the medium term. The Ts trend assumes that ongoing tensions between Europe and Russia would persist and escalate in the foreseeable future, leading to a cessation of gas imports and consequently higher power prices in Europe. The three energy renovation scenarios and the additional three dimensions of socioeconomic and political interventions are summarised in Table 1.

Building construction

The residences in the Netherlands are categorised into five archetypal types: detached houses, semi-detached houses, terraced houses, apartments, and maisonettes[69]. Apartments further encompass gallery apartments, porch apartments, and other apartments. The material intensities (in kg/m^2) for constructing different types of homes are derived from the report[70]. Detailed environmental inventory data for the construction stage are provided in Supplementary Tables 1–5 in the SI. The integrated unitary costs (in €/m^2) for constructing different homes are obtained from Arcadis NV[71], as shown in Supplementary Table 20 in the SI.

Building operation

For the operation of buildings, we consider the energy use and costs associated with household heating and cooling, cooking, domestic hot water supply, electrical appliance usage, and lighting. Home maintenance, however, is not included in the assessment. Homes constructed at different times are categorised into five vintage cohorts, up to 1960, 1961–1980, 1981–2000, 2001–2014, and 2015–2050. Different cohorts of homes vary in insulation levels of envelopes, leading to different thermal efficiencies and, consequently, distinct operational footprints. Building upon our earlier publications[57–59], we determine the heating and cooling demands before and after façade refurbishment for various cohorts of houses by employing building energy simulation with the EnergyPlus software (see Supplementary Tables 6–8 in the SI). The energy needed for per-annum cooking, domestic hot water supply, electrical appliance usage, and lighting is calculated based on the Statistics Netherlands[72] and TABULA database[73](Supplementary Tables 9–11 in the SI). The historic energy costs (Supplementary Table 21) are estimated from Eurostat[74,75] and are further extrapolated based on the two future power price trends from Energy Brainpool[67].

The 3.5 °C and 1.5 °C pathways represent two background energy transition pathways in this study. To avoid complicating the context, we incorporate two foreground housing heating technology transitions based on these two pathways, while heating technology mixes are examined by a sensitivity analysis. Currently, around 90% of households in the Netherlands use natural gas for heating, with only 8% and 2% of the heating demand being satisfied by district heat networks and electricity, respectively[76]. Under the 3.5 °C pathway, we assume that the natural gas-based heating method for the existing housing stock would remain unchanged until 2050, as shown in Supplementary Fig. 1 in the SI. Newly built homes have more efficient heating systems such as heat pumps[77]. The current mix of heating methods for newly built homes was obtained from literature[76], which indicates the following distribution in 2020: 17% electric heat pumps, 25% hybrid heat pumps, 30% district heat network, and 28% natural gas condensing boilers. We assume these proportions for new homes would remain at 2020 levels until 2050 under the 3.5 °C pathway.

The Dutch government plans to phase out natural gas for building heating by 2050[76], implying a reduction in natural gas use from 90% to 0% by 2050. This zero-gas ambition is incorporated into the 1.5 °C pathway in this study (see Supplementary Fig. 1 in the SI). As the gas-based heating systems are retained in the BsL and ReF scenarios, only the ReB scenario represents the zero-gas trajectory, assuming that gas-heated homes would be fully rebuilt by 2050. Biogas production is promoted to reduce natural gas use in old homes. Based on projections that 26–35% of electricity generation in the Netherlands in 2050 would be sourced from biogas[29], we assume that 30% of the current natural gas demand for existing homes would be substituted with biogas by 2050. For newly built homes, a gradual transition of alternative heating technologies is modelled, according to the High Heat Pump scenario from Verhagen et al.[29] and the report[76]. This implies that, by 2050, 52% of the new homes would use electricity heat pumps, 19 % hybrid heat pumps, 23% district heat networks, and 6% with biogas condensing boilers. Detailed unit processes for modelling household energy utilities are provided in Supplementary Table 12 in the SI.

Building energy renovation

The umbrella concept of ‘energy renovation’ includes various options, spanning building envelope improvements, heating, ventilation and air-conditioning system upgrades, and renewable electricity/heat generation system installations, etc.[78]. These diverse options for energy renovation achieve varying levels of energy savings. This study delves into a recently developed PCE system by the H2020 project VEEP[43] designed for both refurbishing existing homes’ facades and constructing new homes’ walls[41]. The PCEs for refurbishment are intended exclusively for use in the ReF scenario. In contrast, another PCE is designated for constructing walls of new homes across all three scenarios. The refurbishment-type PCE employs lightweight aggregate concrete to diminish the structural load of buildings, while the construction-type PCE use regular concrete. Both PCEs incorporate aerogel to ensure their high performance in thermal insulation. A detailed introduction to the PCE system is provided in Supplementary Fig. 2 and Supplementary Tables 13–14 in the SI.

The ReF and ReB scenarios envision the complete renovation and rebuilding of all ageing buildings in the Netherlands by 2050. Three basic rules are applied to guide modelling refurbishment and reconstruction. First, the starting year for renovation and reconstruction is assumed to be 2015, and homes built before 2015 are considered for renovation and rebuilding. Second, only homes standing beyond 2050 are considered for refurbishment and reconstruction. Since the homes refurbished with PCEs in the Ref scenario would not reach their EoL stage within the 2015–2050 timeframe, the recyclability and reusability of refurbishment-type PCEs are excluded. Newly built homes are unlikely to be demolished by 2050, with only a negligible fraction retiring within this timeframe, as modelled using the Weibull distribution to estimate housing stock turnover. The EoL construction-type PCEs are recovered alongside other CDW. Third, priority is given to refurbishing and rebuilding older homes, as they offer greater marginal benefits.

Determining the start of housing energy renovation in the Netherlands is challenging, as varying degrees of such practices have been observed since the early 2000s[79]. The earliest recorded data we could find on the share of the annual building stock undergoing a major renovation in the Dutch residential sector is from 2014, with ~1%[80]. Moreover, the Buildings Performance Institute Europe (BPIE) used 2015 as the baseline year for initiating nationwide housing energy renovation efforts in alignment with the Netherlands’ climate mitigation goals[35]. Accordingly, this study adopts 2015 as the starting point for comprehensive renovation efforts. While recognising the existence of prior renovation activities, the lack of detailed and quantifiable data prevents their inclusion. Given the lack of historic renovation data from 2015 to 2024, a consistent renovation trajectory aligned with certain renovation scenarios for the 2015–2050 period is proposed. This assumption results in ~17 million m² of floor area being renovated annually since 2015. On the other hand, large-scale rebuilding remains an extreme measure that has yet to be implemented. To ensure the comparability between the ReB and ReF scenarios, rebuilding efforts in the ReB Scenario are also assumed to begin in 2015, progressing in parallel with refurbishment activities in the ReF scenario.

The inventory data on the manufacture, transport, and installation of the refurbishment-type PCEs are modified based on our previous studies[57,58]. The footprints of PCEs for new buildings are not separately modelled as they are assumed to be included within the construction and demolition phases of a new building. The production and installation of electric systems such as heating, cooling, ventilation, and other appliances in new buildings are excluded from the scope of this study. Detailed data on energy renovation is presented in Supplementary Section 1.3 of the SI.

Building demolition

During the final phase of a building’s life cycle, demolition involves dismantling key components such as the roof, walls, ceiling, and bottom plate. Comprehensive inventory data on the use of machines, waste containers, and utilities required for building demolition is gathered from the study[81], as shown in Supplementary Table 15 in the SI. The integrated unitary cost for the demolition is subsequently estimated from Arcadis NV[71], as shown in Supplementary Table 22 in the SI.

Waste generation and treatment

The waste intensity data for estimating waste generation from construction, demolition, and renovation activities are provided in Supplementary Table 16 in the SI. Various waste treatment operations are discussed, ranging from the least preferred option of landfill to more favoured methods such as energy recovery, downcycling, recycling, upcycling, and the most encouraged approach in this study—preparation for reuse. The definition of these treatment options is drawn from the Waste Framework Directive[82] and further clarifications are provided from other studies[51,83]. Waste treatment encompasses two main operations: recovery and disposal. In this study, landfills are the sole disposal option, while recovery is a comprehensive concept that embraces energy recovery, downcycling, recycling, upcycling, and preparation for reuse.

Wastes possessing high calorific value, such as waste timber, are directed to combustion plants for energy recovery. The rest of the recovery approaches aim for material recovery. The critical differentiation among downcycling, recycling, and upcycling lies in whether the waste undergoes reprocessing for a purpose or value that is lower, original, or higher, respectively[83]. Besides metallic wastes holding high economic value, mineral wastes generated from buildings, like concrete, are commonly downcycled for road engineering and site elevation[34]. However, there exists untapped potential for efficient recycling for almost all CDW. The EC strategy delves into the assessment of recycling typical CDW, while also exploring various instances of upcycling, encompassing processing bricks[81], ceramics and tiles[84], glass[57,59,85] into supplementary cementitious and insulation materials. Specific building components could be carefully disassembled and repaired to extend their lifespan in a new building[51]. Per the reusability discussed in the report[86], we consider the reuse of building components, including concrete and stony elements, bricks, ceramics and tiles, ferrous and non-ferrous metals, flat glass, timber components, insulation panels, and gypsum plasterboards. The data on historic CDW management covers the period from 2015 to 2020, while projections for future waste management start from 2021. The detailed assumptions for the share of each waste treatment operation in the two material circulation strategies are illustrated by Supplementary Table 17 and Supplementary Figs. 3, 4 in the SI. The sources of the environmental and economic inventory data are provided in Supplementary Tables 18, 19 and 23, respectively. The detailed environmental inventory data are provided in the Supplementary Data 1.

Housing stock and material flow modelling

The MFA is an approach based on the law of conservation of mass to assess the metabolism of materials in a region[87]. A dMFA model is used to characterise the housing stocks (in m^2 of habitable floor area) and material flows (in kg) of the residential sector in the Netherlands over the period between 2015 and 2050. Our prior research uses a top-down stock-driven model[41] to investigate the dynamics of building energy renovation (as illustrated by the ReF scenario in this study) by examining three key parameters: population, floor area per capita, and building lifetime probability distribution. That model involves the input of the construction floor area (in m^2) and the output of the demolition floor area (in m^2), based on which material flows and waste flows are estimated accordingly (Supplementary Section 3, SI). Five types of homes are considered. Terraced houses (33.60%) account for the largest share of the Dutch dwellings, followed by maisonettes (24.38%), detached houses (15.98%), apartments (14.65%), and semi-detached houses (11.39%)[41]. It is assumed that this division remains constant over time. Building on this foundation, this study updates the material and waste intensity data and introduces an additional ReB scenario. Data on waste intensities (in kg/m^2) from construction, renovation, and demolition activities is collected from the literature[86,88–90]. The waste composition data (in %) is sourced from the literature[86]. Each waste stream is transformed into secondary raw materials through the allocation factors of each treatment operation in the HR and EC strategies.

Footprint assessment

LCA and LCC are employed to assess the lifecycle-based footprints of each unit process. LCA is a standardised method that assesses the inputs and outputs and the associated potential environmental impacts of a product system during its life cycle[91]. This study adopts a process-oriented LCA approach to quantify the carbon and material footprints for each process, utilising the ecoinvent 3.9 Allocation, Cut-off by Classification database[66]. In contrast to conventional footprint analysis, lifecycle-based carbon and material footprints using a life cycle perspective can comprehensively account for upstream and downstream indirect impacts, thereby preventing the risk of burden shifts[47,56,92]. The carbon footprint is assessed by GHG emissions (in kg CO_2-eq), expressed in terms of Global Warming Potential over 100 years, per the IPCC 2021 impact method[93]. The material footprint is measured using the Total Material Requirement method[40], expressed in kg.

LCC complements LCA by providing a process-based analysis of lifecycle expenditures, aiming to reduce the overall cost of a product[94]. This study employs LCC to evaluate the economic footprint of each unit process involved, expressed in euros (€). Although lacking a standardised definition, the economic footprint can be conceptualised as the direct and indirect economic impacts stemming from specific processes, products, or activities within a region or an entire country[56]. These impacts can be quantified regarding cost[95] or contributions to Gross Domestic Product (GDP)[96]. To assess the economic impacts of building energy renovation, this study considers the direct costs incurred throughout a building's life cycle, including construction, renovation, operation, demolition, and waste treatment. Only real cash flows related to stakeholders at each life cycle stage are accounted for. In adopting this approach, an LCC is undertaken from a hybrid-actor perspective, as proposed by Zhang et al.[58]. This approach integrates various stakeholders throughout the value chain of building energy renovation, such as manufacturers, constructors, homeowners, and recyclers, to enhance cost-effectiveness across all stages of a building's life cycle. Interest rates are applied to discount the annual costs to their net present value as of 2020 (see Supplementary Fig. 5 in the SI). Specifically, the interest rates on household deposits are used to discount operational costs. In contrast, the interest rates on outstanding loans to non-financial corporations are applied to discount costs incurred in other stages[97].

Multifunctional processes, such as downcycling and recycling, exist in the unitary footprint assessment considering waste recovery. The substitution approach is used in inventory modelling to handle the multifunctionality issue by deducting the avoided environmental and economic burdens of producing and transporting virgin materials from the system[98].

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The background data are provided in the Supplementary Information. The life cycle environmental inventory data for life cycle assessment modelling are provided in the Supplementary Data 1. The data underlying the figures in the main text are available in the Source Data. Source data are provided with this paper.

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Chunbo Z., M.H. and A.T. conceived and designed the research; Chunbo Z., R.S., S.Y., T.J.V. and Chi. Z. collected the data; Chunbo Z. analysed the data; R.S., Chi Z., S.Y., B. Sprecher, B. Steubing, X.Y. and T.J.V. validated the data; Chunbo Z., R.S., X.Y. and B. Steubing contributed materials/analysis tools; Chunbo Z., M.H., B. Sprecher, R.S., B. Steubing and A.T. contributed to paper editing and writing.

Competing interests

The authors declare no competing interests.

Additional information

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