Towards circular and energy-efficient management of building stock: an analysis of the residential sector of the Netherlands

Zhang, C.

Chapter 6

Integrated material-energy efficiency renovation of housing stock in the Netherlands: Economic and environmental implications

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Abstract

The Netherlands strives to achieve ambitious targets with regard to circularity and carbon neutrality in the built environment by 2050. Technical and social innovations are required to accelerate developmental progress to meet these ambitions. This paper presents a material-energy efficiency method of retrofitting building stocks with prefabricated concrete elements (PCEs) with high value-added recycled construction and demolition waste (CDW) as feedstock. The objective of this study is to investigate (i) the economic and environmental trade-offs of the PCE system compared to other options using both an actual-value approach and an annualized-value approach and (ii) to what extent circularity and decarbonization goals can be realized if this PCE system is up-scaled to the residential sector. By combining dynamic material flow analysis with life cycle assessment and life cycle costing, this study analyzes both the product-level and nationwide carbon mitigation, cost, and material footprint reduction potential of implementing this PCE system to the Dutch housing stock for the period 2015-2050. In addition to the proposed renovation scenario (REN), two additional scenarios were developed: the baseline business-as-usual (BAU) scenario, which does not apply any renovation strategy, or the rebuilding (REB) scenario in which old buildings are demolished and reconstructed instead of renovation. The key findings are: (i) the actual- and annualized-value approach may lead to different outcomes: this PCE system in the REN scenario achieves better comprehensive benefits in an annualized-value approach whereas shows a clear trade-off using an actual-value approach compared with the BAU scenario; (ii) the likelihood of achieving the circularity goal by 2030 is almost impossible; (iii) the REN and REB scenarios can achieve the goal of 49% carbon mitigation by 2030, however, only the REB scenario can achieve net-zero emissions by 2050. In the REN

scenario, carbon neutrality in the housing sector requires replacing traditional gas-based systems with electricity-based systems and achieving 100% renewable electricity supply nationwide.

Keywords: life cycle assessment, life cycle costing, construction and demolition waste, building energy renovation, material circularity, decarbonization

Abbreviations

3R	Reduce, reuse, and recycle
ADR	Advanced dry recovery technology
BAU	Business-as-usual
CDW	Construction and demolition waste
CRLWCA	Coarse recycled lightweight concrete aggregate
CRSCA	Coarse recycled siliceous concrete aggregate
DGR	Dry grinding and refining system
EC	European Commission
EoL	End-of-life
EU	European Union
FRSCA	Fine recycled siliceous concrete aggregate
FRLWCA	Fine recycled lightweight concrete aggregate
GHG	Greenhouse gas
HAS	Heating-air classification system
LCA	Life cycle assessment
LCC	Life cycle costing
MFA	Material flow analysis
nZEB	Nearly zero energy building
PCE	Prefabricated concrete element
PCE-new	Prefabricated concrete element for new building construction
PCE-refurb	Prefabricated concrete element for existing building refurbishment
REB	Demolition and rebuilding/reconstruction (scenario)
REN	Renovation with PCE (scenario)
RFUA	Recycled fiber wool ultrafine admixture
RGUA	Recycled glass ultrafine admixture
SI	Supporting information
URLWCA	Ultrafine recycled light-weight concrete aggregate
URSCA	Ultrafine recycled siliceous concrete aggregate
VEEP	European Union Horizon 2020 project "Cost-effective recycling of C&DW in high added-value, energy-efficient prefabricated concrete components for the massive retrofitting of our built environment"

6.1 Introduction

The Dutch construction sector is a priority with respect to transitioning towards a circular and carbon-neutral society, because it is responsible for 50% of raw material use, 40% of total energy use, 40% of waste generation, and 35% of greenhouse gas (GHG) emissions in the country (Dijksma and Kamp 2016). The Netherlands already achieved 92% recovery rates for CDW in 1995 and reached 97% recovery in 2018 (CLO 2021). However, most stony CDW is downcycled as back filler for road base construction and site elevation. Only 5% is recycled, in e.g. new concrete production (Zhang et al. 2020b). To improve the material efficiency within the construction sector, the Netherlands launched the program “A Circular Economy in the Netherlands by 2050”, aiming to achieve an interim target of 50% less use of primary raw materials (minerals, fossil fuels, and metals) by 2030, and a long-term goal of a fully circular economy by 2050: efficiently using and reusing materials without any damage entering the environment (Dijksma and Kamp 2016).

Most buildings in the Netherlands remains a poor insulation level. 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 (Staniaszek 2015). In 2018, the Netherlands realized a reduction of GHG emissions of 17% compared to emissions in 1990 (PBL et al. 2020). In the Climate Act, the Netherlands set an ambitious interim target with a total GHG emission reduction of 49% by 2030 and a long-term target of 95% by 2050 compared to 1990 (Government of the Netherlands 2019). For the residential sector, an operational GHG emission reduction of approximately 10 Mt and 20 Mt by 2030 and 2050 is expected, respectively (PBL et al. 2020; EZK 2019). Given these GHG mitigation ambitions, the Netherlands committed to energy neutrality target for the built environment by 2050. This means of 7.5 million dwellings, 80% are to be renovated to energy-neutral levels by 2050, which implies that 170,000 homes are to be renovated per annum until 2050 (Staniaszek 2015). Crucially, making the Dutch housing stock energy-neutral has significant implications for material requirements and waste generation, which may interfere with realizing the aforementioned circularity targets.

Based on the building circularity and energy efficiency framework shown in Figure 1.3 and Figure 1.4, we investigated the potential trade-offs between GHG emission, capital expanse, and material use in the upcoming energy renovation of the Dutch residential sector regarding achieving the circularity and energy neutrality targets. We set a business-as-usual (BAU) scenario (no additional effort to achieve energy neutrality), a rebuilding (REB) scenario (achieving an energy-neutral built environment by demolition and rebuilding energy-inefficient stock), and a renovation scenario (REN). For REN, we focused on the use of recently developed advanced technological solutions, including prefabricated concrete elements (PCEs) made with recycled concrete, glass, and insulating mineral wool.

We analyzed the scenarios via a combination of a dynamic material flow analysis (MFA) of the Dutch building stock and environmental life cycle assessment (LCA) and costing (LCC). This provides insights into prospective GHG reductions, material requirements and waste flows, and investment costs for the scenarios in the Dutch context for the period from 2015 to 2050. By doing so, we explore whether the PCE system would bring about economic and ecological wins. To reduce complexity, the approach had to apply several simplifications. Illustrations are the following. First, we used a limited number of ideal-typical residential building types. Second, we assumed that in the REN scenario refurbishing with PCEs would be the main approach and feasible for all building types. Third, we had to make our assumptions about starting years of large-scale renovation efforts and implementation of nearly zero energy building (nZEB) for new build houses. Fourth, we did not consider the carbon uptake by cement carbonation (Xi et al. 2016; Cao et al. 2020). Fifth, as operational energy accounts for most of the life cycle energy use of a building, we only modeled the development of renewable electricity for the operation phase and electricity used in manufacturing processing was assumed to remain at the 2015 level. Sixth, we used a steady-state costing system and assumed a zero interest rate. Seventh, we did not consider the impacts of building maintenance. Finally, we assumed all old houses are supposed to be renovated or demolished by 2050. However, there is approximately 3% of historical dwellings will never be demolished or renovated for heritage reasons (Sandberg et al. 2016). Our study is a simplified reflection of reality. But despite such limitations, the evaluation still can provide a clear illustration of the main trade-offs between scenarios in realizing the interim and long-term dematerialization and decarbonization ambitions for the Netherlands.

6.2 Materials and Methods

6.2.1 Goal and scope

The goal of the analysis is twofold: (i) to identify the trade-offs between GHG emission, capital expanse, and material use incurred in energy renovation; (ii) to explore the potential pathways in building energy renovation towards the circularity and decarbonization ambitions. By doing this, this study assesses climate impacts (in kg CO_2 eq), costs (in Euros), and material footprints (in kg of primary material extraction) for different scenarios with regards to the energy neutrality of the Dutch housing stock for the period 2015–2050. Here we discuss the goals and scope of the study.

6.2.1.1 Methodological overview

The methodological framework for integrating LCA and LCC with the dynamic MFA is presented in Figure 6.1. Buildings constructed at different times are categorized into five vintage cohorts: (i) up to 1960, (ii) 1961–1980, (iii) 1981–2000, (iv) 2001–2014, (v) 2014-2050. Different cohorts of houses vary in insulation levels of envelopes and heating efficiency, resulting in different operational costs, energy use, and GHG emission performance. The Dutch houses are divided into five archetypical types: detached houses, semi-detached houses, terraced houses, maisonettes, and apartments (Agentschap NL 2011). Apartments include gallery apartments, porch apartments, and other apartments. Terraced houses account for the biggest share of the gross Dutch houses (33.60%), followed by maisonettes (24.38%), detached houses (15.98%), apartments (14.65%), and semi-detached houses (11.39%) (Zhang et al. 2021c). We assumed this division to be constant over time, with a slight expansion of the overall housing stock till 2050 according to the building stock model (Zhang et al. 2021c). Three scenarios were considered: BAU, REB, and REN, which represent different circularity and energy-efficiency strategies. Given the availability of data, 2015 was chosen as the starting year of the assessment.

Assessment at product and country level

The assessment is conducted at both the product and country levels. LCA and LCC are suitable for investigating product-oriented life cycle environmental impacts and costs (Hunkeler et al. 2003). LCA and LCC have been widely used in areas of CDW management (Hossain et al. 2016; Zhang et al. 2020c; Pavlu et al. 2019; Massarutto et al. 2011; Mah et al. 2018; Di Maria et al. 2018) and building energy efficiency (Almutairi et al. 2015; Rodrigues et al. 2018; Minne and Crittenden 2015; Günkaya 2020; Pedinotti-Castelle et al. 2019; Atmaca 2016a, 2016b). At the product level, the LCA and LCC were primarily applied to evaluate the (re)construction, renovation, demolition activities in three scenarios. The life cycle of the PCE system consists of three stages: construction, operation, and demolition. However, LCA and LCC are product-oriented approaches and are not directly able to investigate issues at a regional or national scale. To overcome this drawback, we employed a dynamic MFA model to simulate the turnover of building stock in the Netherlands from 2015 to 2050.

At the country level, a dynamic MFA was conducted to explore the characteristics of the Dutch housing stock. Müller developed a dynamic stock-driven building stock model for simulating inflows and outflows of the Dutch housing stock till 2100 (Müller 2006). In the model, turnover of the housing stock is driven by population, floor area per capita, and building lifetime probability distribution. We adjusted Müller's model with more recent data and additionally established REB and REN scenarios (as illustrated in 5.3.3). The outcome of this model was used as an implementation size factor to scale up the environmental and economic impacts of the PCE system, and the requirements for new build houses in the different scenarios. Based on the flows of the model, we estimated the CDW generation and material requirement in three scenarios. In addition, according to the stock information, we simulated the operational energy use according to the vintage cohorts of the housing stock. At the country level, we also additionally considered changes over time in GHG emissions and material footprints of electricity supply, and the operational energy use for heating and cooling, cooking, hot water supply, electrical appliance use, and lighting.

Calculations of actual-value approach and annualized-value approach

We express these indicators using an actual value approach and an annualized-value approach. At the product level, the actual-value approach calculates the GHG emissions, costs, and material footprints of (re)constructing and operating a new or existing house for 36 years (2015–2050); at the country-level, it adds up actual GHG emissions, costs, and material footprints of the energy use of the Dutch housing stock and construction and demolition activities each year to a total in that year for the period 2015–2050.

At the product level, the annualized-value approach calculates the operational energy use the same way as the actual-value approach but distributes GHG emissions, costs, and material footprints, which occur in the construction and demolition phases, as annualized values per year per m^2 per housing type over the lifetime of a house. The annualized country-level results in a year between 2015 and 2050 can be obtained by multiplying annualized GHG emissions, costs, and material footprints of construction, and demolition activities per m^2 in that year with the total m^2 per type of building present in that year to a total. In the annualized-value approach, the annualized construction and demolition impacts and costs of an existing house were also accounted for till this house is demolished.

The annualized-value approach is more suitable for comparing scores for a sound functional unit, such as the impacts and costs per m^2 floor space in use per year, including impacts and costs of the construction phase and benefits of recycling and reuse at the end-of-life (EoL) stage. The actual-value approach provides insights regarding when impacts and costs occur and when initial impacts and costs of refurbishing are compensated by lower impacts and costs in the use phase. Illustrations of these two approaches can be found in the supporting information (SI).

Evaluations of the 2030 and 2050 circularity goals

Based on the country-level actual values, we further analyzed whether the proposed PCE system can realize the circularity goals. Regarding the circularity goal, the REN scenario assumes that sufficient secondary materials are available. Realistically, however, the supply of secondary raw materials might be insufficient to support extensive energy renovation, especially secondary raw materials made from emerging materials, such as lightweight concrete waste. We further considered the supply-demand conditions of secondary raw materials in the realization of the circularity goal. The Circular Economy Program for the Netherlands 2050 proposed a preliminary interim target of 50% less use of material footprints (minerals, fossil fuels, and metals) by 2030 and a long-term goal of a fully circular economy by 2050 (Dijksma and Kamp 2016). This program is rather general in its formulation. For instance, it does not specify a base year, nor does it quantify target volumes for the construction sector for the 2030 and 2050 goals. In consultation with the Ministries of Infrastructure and Environment and Economic Affairs and Climate Policy, Potting et al. (2018) set 2014 as the base year. Considering the temporal scope of our system, we set 2015 as the base year. For the 2050 circularity goal, the Netherlands is supposed to achieve a fully circular economy, qualitatively defined as 'efficient use of material and high-grade reuse of secondary materials while without yielding any harmful emissions into the environment (Dijksma and Kamp 2016). In the EU's Waste Hierarchy, recovery comprises recycling and downcycling, in which recycling represents a high value-added treatment method (EC 2008a). Therefore, we measured the 2050 goal in a simple way via recycling rate and material carbon footprint. The REB and BAU scenarios were assumed to have an identical recycling system, which is in accordance with the real situation of how each fraction in CDW is treatment in the Netherlands (given in the supporting information(SI)). In the REN, concretes waste, glass waste, and insulation mineral wool waste were assumed cost-effectively recycled through advanced ADR, HAS, and DGR systems.

Evaluations of the 2030 and 2050 decarbonization goals

The country-level actual-value results were also used to discuss the realization of the circularity goals. The Netherlands and the EU both set decarbonization goals to facilitate the transition to a carbon-neutral society. The EU represented its member states to commit to reducing GHG emissions by at least 40% by 2030 and by 80%–95% by 2050 compared to 1990 (EZK 2019). In the Climate Act, the Netherlands set an ambitious interim target with a reduction by 49% of gross national emission by 2030 and a long-term goal of 95% by 2050 (Government of the Netherlands 2019). The associated carbon budget was allocated to the Dutch residential built environment. To comprehensively reflect the thermal insulating features of the panels, ideally one would consider both heating and cooling demand for each house. However, regarding the real household cooling demand in the Netherlands, air conditioners are usually installed in the non-residential sector and only 6% of all dwellings have an air conditioning system (Menkveld and Beurskens 2009). In addition, energy demand for cooling accounts for less than 1% of electricity use in the Dutch housing sector (PBL 2018). Therefore, cooling was not taken into account in the evaluation of realizing the carbon-neutral goal.

The emissions from the built environment only include emissions from natural gas and electricity use for heating, cooking, hot water supply, electric appliance use, and lighting. Moreover, in the EU, new buildings constructed after 2020 must meet the standards of nZEB (EC 2010). Two nZEB solutions, in which thermal transmittance of each housing element were introduced, were simulated in three scenarios to explore how the passive energy efficiency approach can influence GHG emissions.

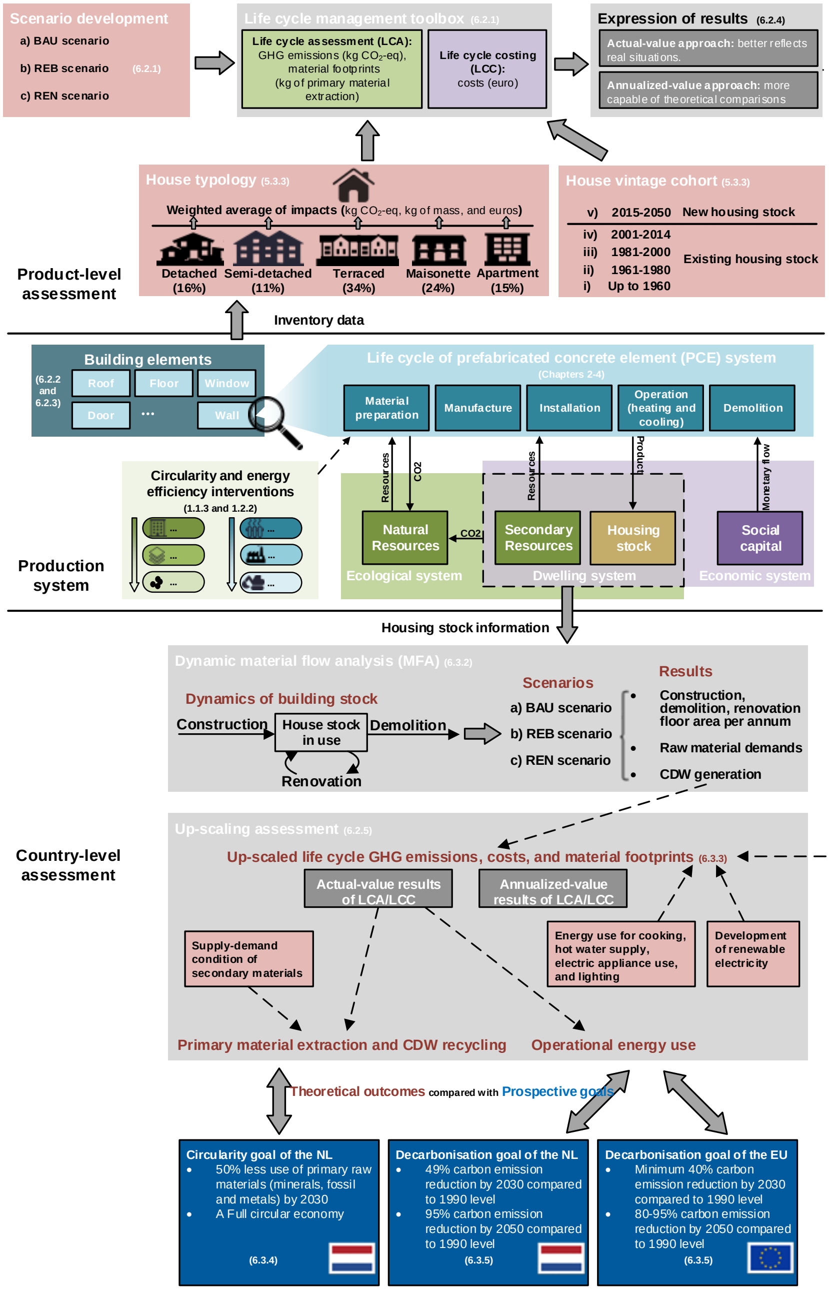


Figure 6.1 Methodological framework of integrated life cycle assessment and life cycle costing with dynamic material flow analysis. BAU: business-as-usual, EU: European Union, NL: The Netherlands, REB: demolition and rebuilding, REN: refurbishment with the PCEs.

6.2.1.2 Scenario development

Three scenarios were developed in this study: BAU, REB, and REN. The characteristics of the three scenarios are presented in Table 6.1. The BAU scenario (i) uses baseline PCE-new, which only includes virgin materials, for constructing walls of new buildings; (ii) does not implement any renovation method for existing buildings; and (iii) does not implement any reuse strategies.

The REB scenario is similar to the BAU scenario. The difference is that in the REB scenario old buildings are demolished early and replaced with new buildings with higher energy efficiency performance, so that by 2050 all houses are constructed after 2014, with equal amounts of houses rebuilt per year starting with the oldest vintage cohorts.

The REN scenario assumes that all existing buildings will be refurbished by 2050 using green PCE-refurb, with equal amounts of houses being refurbished per year starting with the oldest vintage cohorts. The scenario assumes (i) that an innovative recycling system is applied to produce high-quality secondary materials; (ii) application of green PCE-new for building new houses and green PCE-refurb for refurbishing old buildings and (iii) that green PCE-refurb is reused at its EoL stage.

Table 6.1 Characteristics of three scenarios for product- and country-level assessment

Scenario	At building level	At element level	At material level
BAU	**At product level:** New building: (i) is implemented with the baseline PCE-new, which do not contain secondary raw materials and use expanded polystyrene as insulation in walls; (ii) of which other envelopes (floors, roofs, windows) have high insulation level; (iii) uses air-conditioning and heat pump for space cooking and heating. Existing building: (i) with poor insulation level envelopes; (ii) uses air-conditioning and condensing boiler for space cooling and heating; (iii) is demolished when become obsolete; **At country level:** The up-scaled assessment additionally considered (i) the influence of developing renewable electricity over time; (ii) operational energy use for	**At product level/ country level:** Each component of the baseline PCE-new is recovered through traditional waste treatment systems.	**At product level:** Only virgin raw materials are used. **At country level:** Only primary raw materials are used.

	cooking, hot water supply, electric appliance use, and lighting.		
REB	**At product level:** New building: same as the BAU. Existing building: (i) in poor insulation level of envelopes; (ii) uses air-conditioning and condensing boiler for space cooling and heating; (iii) is demolished early and then to rebuild conforming to the requirement of a new building. **At country level:** Same as the BAU.	**At product level/ country level:** Same as the BAU.	**At product level/ country level:** Same as the BAU.
REN	**At product level:** New building: (i) is implemented with green PCE-new, which contain high volumes of secondary raw materials and use aerogel as insulation in walls; (ii) of which other envelopes have high insulation level; (iii) uses air-conditioning and heat pump for space cooking and heating. Existing building: (i) in poor insulation level of envelopes; (ii) uses air-conditioning and condensing boiler for space cooling and heating; (iii) is implemented with green PCE-refurb to over-clad the wall for optimizing the thermal performance as well as prolonging the lifetime. **At country level:** Same as the BAU.	**At product/country level:** PCE-refurb is dismantled for reuse; each component of a green PCE-new is recovered through advanced waste treatment systems.	**At product level:** Secondary raw materials are used to substitute certain portions of primary raw materials in the manufacturing of green PCE-new and PCE-refurb. **At country level:** Secondary raw materials are assumed sufficiently supplied.

6.2.1.3 Functional unit of the LCA and LCC

The functional units for the LCA and LCC were: provisioning the service of habitable floor area. The product-level assessment aims to evaluate how the PCE system improves the thermal performance of a building. Therefore, only the energy savings for heating and cooling were considered at the product level. At the country level, the habitable surface not only comprises heating and cooling comfort but also includes cooking, hot water supply, electrical appliance use, and lighting.

- The product-level functional unit: maintaining the indoor thermal comfort by active heating and cooling of 1 m^2 habitable floor area per year of (i) existing houses per vintage group (BAU scenario), (ii) demolished and rebuilt houses (REB scenario), and (iii) refurbished houses with green PCE-new and green PCE-refurb (REN scenario) in the Netherlands.

- The country-level functional unit: providing the total amount required habitable floor area in the Netherlands while maintaining the indoor thermal comfort by active heating and cooling per year for the period 2015-2050. As indicated, we added also the energy use for cooking, hot water supply, electrical appliance use, and lighting in the country-level assessment.

6.2.2 Life cycle inventory of GHG emissions, costs, and material footprints

In this section, we discuss the method used to collect data for the central parameters in this study: GHG emissions, costs, and material footprints. Given the scenarios presented previously, the following elements must be considered:

1. Three types of PCE panels: (embodied) GHG emissions, costs, and material footprints for (i) baseline PCE-new, used for constructing the wall of new houses in the BAU and REB scenario; (ii) green PCE-new, used for new houses in the REN scenario; (iii) green PCE-refurb, used for refurbishing existing houses in the REN scenario;

2. Existing houses: (embodied) GHG emissions, costs, and material footprints for constructing per m^2 of existing house, and gas and electricity use per vintage per m^2/year in the operation phase;

3. New and rebuild houses: (embodied) GHG emissions, costs, and material footprints per m^2 of rebuild houses in the production phase, and gas and electricity use per m^2/year in the operation phase;

4. Refurbished houses: (embodied) GHG emissions, costs and material footprints per m^2 of refurbishing with PCE-refurb in the production phase, and gas and electricity use per m^2/year in the operation phase;

5. Other unit processes: costs related to electricity and gas use, house demolition, and CDW generation and recycling, nZEB standards.

Below, we explain the approach for obtaining this inventory information. Detailed inventory data are presented in the SI. For the heating and cooling of Dutch houses, we assumed the use of gas boilers or electric heat pumps. For electricity, we assumed changes in the electricity mix for the Netherlands, leading to carbon-neutral electricity provision in 2050. The Supporting Information provides more detail.

6.2.2.1 PCE panels: baseline PCE-new, green PCE-new and green PCE-refurb

The proposed PCE system presents a potential solution for simultaneously realizing the circularity and carbon neutrality goals. From the waste prevention aspect, prefabricated construction has been seen as a solution to minimize CDW arising in the construction phase (Tam et al. 2006), as well as during the EoL phase owing to the dismantlability of the precast components. In the REN scenario, we discern two PCE systems: green PCE-new and PCE-refurb. was assumed as the insulating layer for green PCE-refurb and green PCE-new in the REN scenario. The main difference is that the green PCE-new is implemented in new buildings and uses normal-weight concrete as a component and cannot be reused, whereas green PCE-refurb is implemented in existing buildings, use lightweight concrete as a component, and can be reused (see Figure 6.2). For new buildings in the BAU and REB scenarios, a reference baseline PCE-new was used, which has the same dimensions as the green PCE-new but only contains primary raw materials and uses expanded polystyrene as insulation materials.

The hypothetical lifetime of the baseline/green PCE-new is determined by the average lifetime of a new house, which is 120 years (Zhang et al. 2021c). It is not yet clear whether the PCE-new can be reused. The green PCE-refurb are reusable after the end of life of a refurbished house (Zhang et al. 2021a). Hence, in this study, we assumed that only green PCE-refurb were reused when the refurbished houses were demolished. At the material level, recycled materials are assumed to be used to manufacture the green PCE-new and green PCE-refurb in the REN scenario to reduce the depletion of raw materials, as described in earlier studies (Moreno-Juez et al. 2020; Zhang et al. 2019a; Gebremariam et al. 2020; Zhang et al. 2020a, 2021a, 2021b). The GHG emissions, costs, material footprints related to the three PCEs, baseline PCE-new, green PCE-refurb, and green PCE-new are all based on this earlier work and illustrated in the SI.

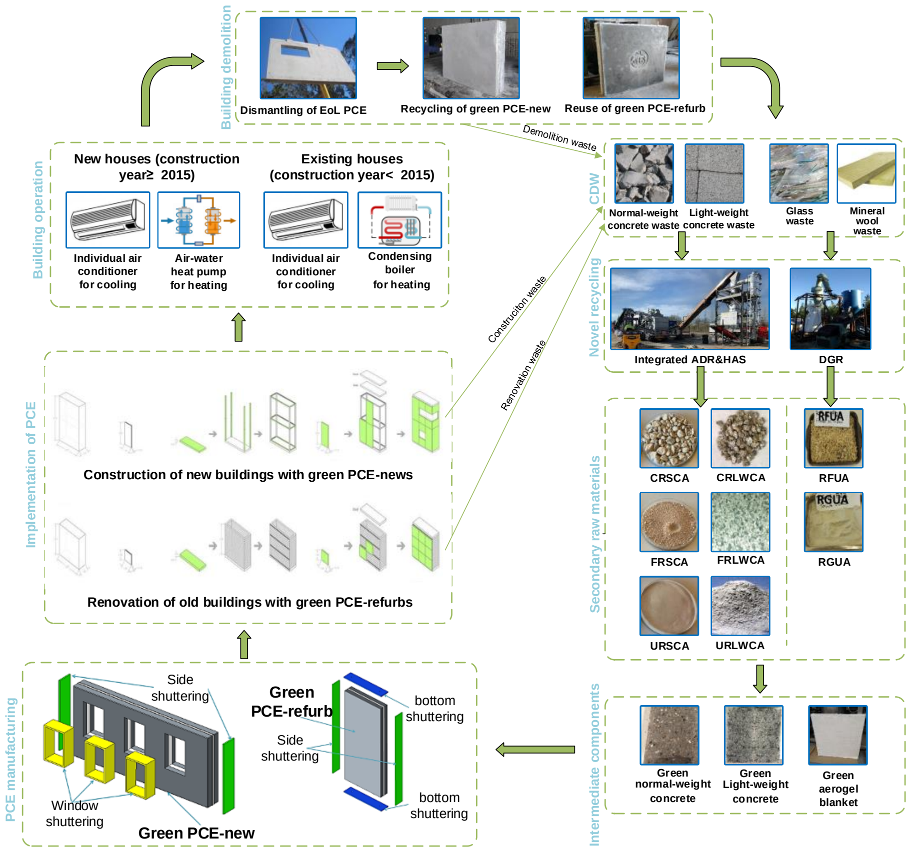


Figure 6.2 Technological route of the novel PCE system for the REN scenario. ADR: Advanced dry recovery system; CDW: construction and demolition waste; CRLWCA: coarse recycled light-weight concrete aggregate; CRSCA: coarse recycled normal-weight concrete aggregate; DGR: Dry grinding and refining system; FRLWCA: fine light-weight recycled concrete aggregate; FRSCA: fine siliceous normal-weight recycled concrete aggregate; HAS: Heating-Air Classification System; PCE-new: prefabricated concrete element for new building construction; PCE-refurb: prefabricated concrete element for existing building renovation; RFUA: recycled fiber wool ultrafine aggregate; RGUA: recycled glass ultrafine aggregate; URLWCA: ultrafine recycled light-weight concrete aggregate; URSCA: ultrafine recycled siliceous normal-weight concrete aggregate.

6.2.2.2 Existing houses: construction, and operation phase data

For existing houses, we need to have insight into the GHG emissions, costs, and material footprints of construction, and energy requirements in the operation phase. The GHG emissions and material footprints of constructing per 1 m^2 of existing houses were assumed the same as that of new houses. Construction costs of existing houses is 711.60

€/m^2 with an uncertainty range of (541.20, 881.56). It was adjusted based on the current construction costs and historical house price index (Arcadis 2017; CBS 2021a).

The operational energy for heating (assumed by condensing gas boilers) and cooling (assumed by individual air conditioners) by vintage per m^2/year, and energy for cooking, hot water supply, electric appliance use, and lighting in general. We assumed that the insulation level of the walls of a house was determined by the vintage of construction. Following a report of PBIE, we divided the Dutch houses into five cohorts based on construction vintages of houses: (i) up to 1960, (ii) 1961–1980, (iii) 1981–2000, (iv) 2001–2014, and (v) since 2015 (Economidou 2011). In general, the thermal performance of walls of residential buildings improves over time. The thermal transmittance of the wall presents an increasing trend from 2.70 W/(m ^{2}K) in the 1960s to 0.40 W/(m ^{2}K) in the 2000s (Economidou 2011). The thermal transmittance of the wall of existing buildings constructed up to 1960 is 2.70 W/(m ^{2}K); buildings constructed in 1961 to 1980 is 1.00 W/(m ^{2}K); that in 1981 to 2000 is 0.60 W/(m ^{2}K); that in 2000 to 2014 is 0.40 W/(m ^{2}K).

The operational energy demand for space heating and cooling of houses of different vintage cohorts was estimated. We estimated the yearly heating and cooling requirements per m^2, assumed to be provided by a traditional condensing gas boiler and an individual air conditioner using electrical power (TABULA 2017). We conducted dynamic thermal simulations to obtain the yearly heating and cooling demand of houses in the climate condition of the Netherlands. The yearly heating and cooling demands for exiting housing cohorts range from 52.17–99.80 and 1.31–1.85 kWh/(m ^{2}annum), respectively. The gas and electricity consumption for cooking, hot water supply, electric appliance use, and lighting are 83.92 MJ/(m ^{2}annum) and 0.0241 kWh /(m ^{2}annum), respectively, according to Statistics Netherlands (PBL 2018). We further linked the yearly energy uses with the unit processes to estimate the consequent GHG emissions, costs, and material footprints. We refer to the detailed inventory data in the SI.

6.2.2.3 New and rebuild houses: production (construction) and operation phase data

The EU Directive 2010/31/EU required that the member states must ensure that new buildings constructed after 2020 meet the requirements of nZEB (EC 2010). As there is no evidence of large-scale renovation in the Netherlands in the past, for the sake of simplicity, we assumed that the Netherlands could start with renovation for low-energy use in 2015 and build new houses according to nZEB standards in 2015. Thus, new houses in this assessment refer to houses that have been constructed since 2015. These houses have excellent insulation levels and use efficient heating systems. Houses constructed since 2015 were assumed to be equipped with gas-free heating systems, i.e. an air-water heat pump (TABULA 2017).

Construction phase: GHG emissions, costs and primary material use per m²

For material requirements regarding the construction of new houses, Arnoldussen et al. reported the material intensity for constructing 1 m^2 of different types of houses in the Netherlands (Arnoldussen et al. 2020). Based on the stock share of each type of house and emission intensities, the weighted material intensities for constructing a habitable floor area are as follows, 1,198.52 kg/m^2, 36.57 kg/m^2 of wood, 62.60 kg/m^2 of steel, 25.20 kg/m^2 of glass, 18.57 kg/m^2 of insulation, and 12.27 kg/m^2 of gypsum, amounting to 1,353.74 kg/m^2 in gross. We linked these material intensities with primary material extraction indicators and unit emission indicators from the Ecoinvent database to obtain the GHG emission and material footprint per m^2. The weighted emission and material footprints for constructing a habitable floor area are 338.87 kg CO_2 eq/m^2 and 6342.27 kg/m^2. We assumed that the manufacturing impacts of heat pumps were included in these emissions and resource uses. Arcadis NV reported construction costs for different types of houses in the Netherlands (Arcadis 2017). From this, a weighted average-based construction costs according to the share per housing type to stock is estimated at 904.18 euros/m^2 with an uncertainty range of 687.66–1120.14 euros/m^2. We assumed that the costs of heat pumps and air conditioners were included in these costs.

In the BAU and REB scenarios, we assumed that the impacts and costs of the PCE-new facades are included in the aforementioned data. The REN scenario however uses green PCE new instead of baseline PCE new for new build houses. For new build houses in the REN scenario hence we added the difference in impacts and costs between baseline PCE new and green PCE new. This data was taken from previous work (Zhang et al. 2020a). In short, each m^2 of habitable floor area requires a weighted average-based share in gross house stock across the different housing types (0.57 m^2) of baseline/green PCE-new for cladding the façade of new houses (Zhang et al. 2021c). The production emission, cost, and material footprint of baseline PCE-new for per m^2 floor area are 98.03 kg CO_2 eq/m^2, 285.40 euros/m^2, and 463.85 kg/m^2, respectively. For the green PCE-new, 142.95 kg CO_2 eq/m^2, 286.97 euros/m^2, and 415.69 kg/m^2, respectively. In the REN scenario, the impacts and costs of construction and demolition of 1 m^2 new house are hence modified by adding the differences (44.92 kg CO_2 eq/m^2 of GHG emissions, 1.57 euros/m^2 of costs, and –47.89 kg/m^2 of primary material extractions) of the green PCE-new from the baseline PCE-new. Consequently, the GHG emissions, costs, and primary material extractions of constructing per m^2 of new habitable floor area in the REN scenario is 383.79 kg CO_2 eq/m^2, 937.58 euros/m^2, and 6294.10 kg/m^2.

Use phase: energy requirements per m²/year

Regarding energy requirements of new houses, the yearly heating and cooling demands for new houses constructed with baseline PCE-new are 29.25 kWh/(m^2annum) and 3.35 kWh/(m^2annum), respectively. For houses constructed with green PCE-new, the heating and cooling demands are 25.90 kWh/(m ²annum) and 3.84 kWh/(m ²annum), respectively. For new houses, energy cooking, hot water supply, electric appliance use, and lighting were assumed using electricity, which is 23.33 kWh/(m ²annum) (PBL 2018). Associated GHG emissions, costs, and primary material depletions were calculated based on energy uses. The material intensities, yearly electricity use, and related costs per m^2/year for newly built houses in detail are presented in the SI.

6.2.2.4 Refurbished houses: production (refurbishing) and operation phase data

We refer to existing buildings as houses built before 2015. Compared with new buildings, elements of existing buildings have a lower insulation level.

Production phase: GHG emissions, costs and material use per m^2

Refurbishment assumes that the exterior walls are over-cladded by green PCE-refurb. The GHG emissions, costs, material footprints for producing the amount of green PCE-refurb (0.57 m^2) for refurbishing per floor area are modified based on our previous study Zhang et al. (2021a), which are 101.28 kg CO_2 eq/m^2, 119.77 euros/m^2, and 387.86 kg/m^2, respectively.

For annualized values calculations, the green PCE-refurb are assumed to be reused when the refurbished houses are demolished in the annualized-value approach. The reused green PCE-refurb are assumed to be repaired and then used to refurbish other houses. We assumed a 10% loss of mass when a green PCE-refurb is dismantled and reused (Zhang et al. 2021a). Following this, the reuse of green PCE-refurb in the REN scenario was modeled as reducing 90% of the impacts from material production, PCE-refurb manufacture, and PCE-refurb disposal. We further assume that refurbishing will extend the lifetime of the building by 15 years (Duurzaam Gebouwd 2014).

Use phase: energy requirements per m^2/year

After refurbishment, the thermal insulation level of the walls was improved with a range of 0.14–0.20 W/(m ²K)), leading to lower heating and cooling requirements per m^2/year. The thermal transmittance of the refurbished wall of existing buildings constructed up to 1960 is 0.203 W/(m ²K); that in 1961 to 1980 is 0.180 W/(m ²K); that in 1981 to 2000 is 0.161 W/(m ²K); that in 2000 to 2014 is 0.142 W/(m ²K). The consequent heating and cooling demands per annum are 44.67–46.68 and 2.29–3.35 kWh/(m ²annum), respectively. The energy requirements for cooking, hot water supply, electric appliance use, and lighting remain the same. The associated GHG emissions, costs, and material footprint were estimated according to yearly energy use. Detailed environmental and economic inventory data for refurbishing are given in the SI.

6.2.2.5 Other inventory data

The Dutch housing stock, consisting of a mix of existing, refurbished and new build houses need a mix of gas and electricity for heating and cooling and other purposes. We used Ecoinvent 3.4 to assess GHG emissions, costs, and primary material uses. The costs of space heating by gas boilers were estimated at 0.010 euro/MJ and heat pumps were estimated at 0.011 euro/MJ, respectively, and assumed to be constant. For electricity supply, we assumed changes in the electricity mix for the Netherlands, leading to carbon-neutral electricity provision in 2050 (see the SI). Costs for electricity were estimated at 0.21 euro/kWh and assumed constant (Eurostat 2020).

In the different scenarios, at different moments in time, houses are demolished. In this study, we only consider the demolition impacts of new houses. For demolition, the carbon emission at the demolition stage is usually assumed 10% of the construction emission (Lu and Wang 2019). Thus, the demolition emission is 33.89 kg CO_2 eq/m^2. The demolition costs of a house are dependent on the scale of the demolition project and the amount of hazardous asbestos. The average demolition cost of buildings constructed after 2000 is 39.50 euro/m^2 with an uncertainty range of 31.00–48.00 euro/m^2; buildings constructed before 2001 have a demolition cost of 72.00 euro/m^2 with a range of 40.00–104.00 euro/m^2. Primary material use of demolition is 1.94 kg/m^2, excluding disposal of CDW.

Regarding the circularity goal, we estimated the generation of construction waste, demolition waste, and renovation waste from the Dutch housing sector and associated secondary raw materials. The waste intensities for per m^2 of construction, demolition, renovation per floor are 40.61 kg/m^2, 1,208.27 kg/m^2, and 30.61 kg/m^2, respectively (Zhang et al. 2021c). The recycling rate of each CDW in the Netherlands was estimated based on the study (Mulders 2013).

As for the decarbonization goals, there is however no defined nZEB standard. Two databases ZEBRA2020 (2020) and TABULA (2017) proposed preliminary nZEB standards for the Netherlands (given in the SI), including the requirement of thermal transmittance and heating system. To reflect the extent to which the nZEB solution can facilitate the residential sector to achieve the decarbonization goals, we compared new buildings implemented with the PCE-new system from this study with the new buildings with the insulation requirement of the two databases.

6.2.3 Life cycle environmental and economic impact assessment

In terms of impact assessment, we further evaluated GHG emissions, costs, and primary material extraction incurred from the construction, operation, and demolition phases at a temporal and country-wise scale. GHG emissions were expressed in GWP100 according to the report of IPCC (2007). Material footprints were measured in kg of total primary material requirement (Mostert and Bringezu 2019). The costs were calculated in euros. Given the current near-zero interest rates (De Nederlandsche Bank 2020), future costs were not discounted. The LCC was conducted from a hybrid perspective (combined perspective of a consumer and a manufacturer) to investigate the real cash flows incurred (Zhang et al. 2021a).

6.2.3.1 Impacts over time of (re)building, refurbishing, demolishing, and energy use

Because we calculated both environmental and economic parameters via an actual-value and an annualized-value approaches, in Figure 6.3, we illustrate the timing of activities in the different scenarios. This study takes 2015 as the time for prospective policy interventions, thus impacts and costs that occurred before 2015 were seen as "sunk costs" and were not considered (Fuller and Petersen 1995). The REN scenario assumes that all existing buildings will be refurbished by 2050, with equal amounts of houses being refurbished per year. Refurbishment is assumed to start with the building cohort constructed in the oldest vintage. The REB scenario follows a similar pattern, with demolition and reconstruction rather than refurbishment. Further, in all scenarios, including BAU, some housing cohorts reach their natural end of life and are demolished and rebuilt. From these findings, we derived three phases characterized by different activities: (re)building or refurbishment, use/operations, and demolition. The longest period is the operation phase with operational impacts due to heating, cooling, etc. Construction and demolition activities usually require 1–2 years. The construction impacts of a new building are accounted for at the beginning of each year, and demolition impacts are incurred at the end of each year. Operational costs and impacts incurred for the period are always accounted for. While the costs and impacts of construction and demolition were handled differently by using actual-value and annualized-value approaches, as shown in Table 6.2. The differences are further elaborated in the next section.

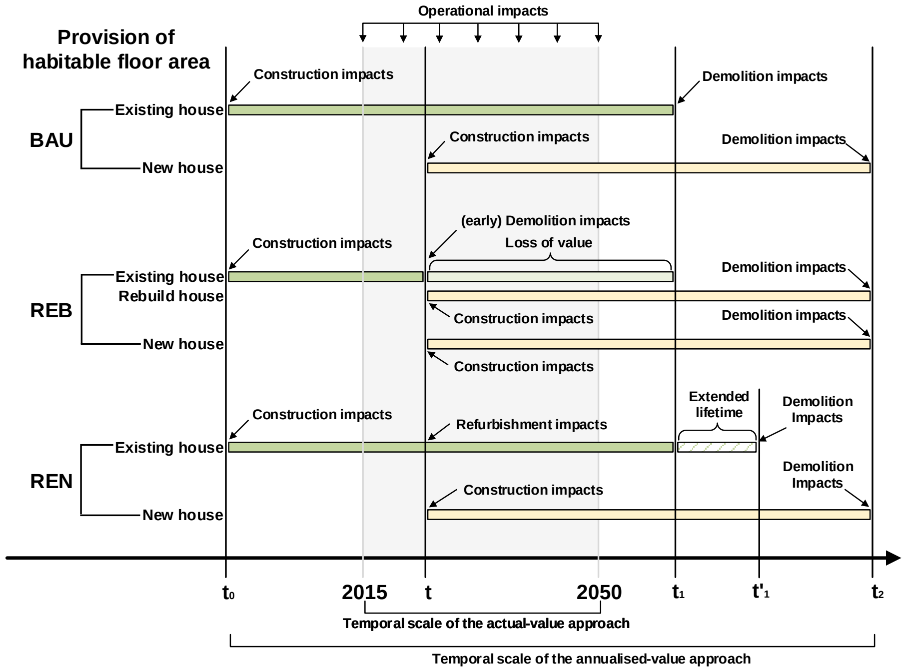


Figure 6.3 Illustration of actual and annualized impacts (GHG emissions, costs, and material footprints) of existing buildings and new buildings in three scenarios. Construction impacts include material production and use of labor, energy, facilities. In the figure, *t* is a snapshot of a discrete year between the temporal scale (2015, 2050), t_0 is the discrete year of construction of the hypothetic existing house, t_1 is the discrete year of demolition of a hypothetic existing house, t_1' is the discrete year of demolition of the hypothetic existing house after refurbishment, t_2 is the discrete year of demolition of a hypothetical new house.

Table 6.2 Costs and impacts of construction and demolition in the actual-value approach and annualized-value approach

	Actual-value approach	Annualized-value approach
Construction	Costs & impacts < 2015 were neglected/irrelevant.	Costs & impacts < 2015 were considered.
	Costs & impacts within 2015-2050 were considered.	Costs & impacts within 2015-2050 were considered.
	Costs & impacts >2050 were neglected/irrelevant.	Costs & impacts >2050 were neglected/irrelevant.
Demolition	Costs & impacts < 2015 were neglected/irrelevant.	Costs & impacts within < 2015 were neglected/irrelevant.
	Costs & impacts within 2015-2050 were considered.	Costs & impacts within 2015-2050 were considered.

	Costs & impacts > 2050 were neglected/irrelevant.	Costs & impacts > 2050 were considered.

6.2.4 Actual-value and annualized-value approach at a product level

The results of the LCA and LCC were expressed in actual and annualized values. The actual-value approach was used to analyze whether the circularity and decarbonization goals at specific moments in time are realized, while the annualized-value approach was applied for comparing different production systems. Based on Figure 6.3 and Table 6.2, the actual product-level impacts of the three scenarios are estimated using Eq. (1). As it can be seen, only costs and impacts of (re)construction, operation, and demolition activities incurred for the period 2015-2050 were considered in the actual-value approach.

The annualized-value approach is more complex. Until 2014, the stocks of existing houses in the three scenarios were the same. Consequently, the construction impacts and costs of existing buildings were incurred at the same time points in the three scenarios. Due to rebuilding and refurbishment, the construction and demolition impacts of some existing houses in the REB and REN scenarios would occur earlier and later, compared with the BAU scenario. Because the time value of money was not considered, the gross impacts of demolition of existing housing stock are identical. However, if annualized-value approach accounting was applied, lifetime extension leads to lower annualized impacts of construction and demolition of existing houses. Similarly, early demolition leads to higher annualized impacts and costs of construction and demolition of existing houses. Construction costs and impacts of existing houses were regarded as sunk ones in the actual-value approach but were considered in the annualized-value approach using Eq. (2).

$$\textit{Actual product} - \textit{level impacts} = \begin{cases} I_{O(an)}^{(exi)} + I_D^{(exi)}, & \textit{existing house in BAU} \\ I_{O(an)}^{(exi)} + I_D^{(exi)}, & \textit{exsting house in REB} \\ I_{O(an)}^{(ren)} + I_R^{(exi)}, & \textit{exsiting house in REN} \\ I_C^{(new)} + I_{O(an)}^{(new)}, & \textit{new house in BAU, REB, REN} \end{cases} \quad (1)$$

$$\textit{Annualised product} - \textit{level impacts} = \begin{cases} I_{O(an)}^{(exi)} + \frac{I_C^{(exi)} + I_D^{(exi)}}{t_1 - t_0}, & \textit{existing house in BAU} \\ I_{O(an)}^{(exi)} + \frac{I_C^{(exi)} + I_D^{(exi)}}{t - t_0}, & \textit{exsting house in REB} \\ I_{O(an)}^{ref} + \frac{I_R^{(exi)}}{\left(t_1' - t\right)} + \frac{I_C^{(exi)} + I_D^{(exi)}}{t_1' - t_0}, & \textit{exsiting house in REN} \\ I_{O(an)}^{(new)} + \frac{I_C^{(new)} + I_D^{(new)}}{t_2 - t}, & \textit{new house in BAU, REB, REN} \end{cases} \quad (2)$$

where t is a snapshot of a year between the temporal scale (2015, 2050), t_0 is the year of constructing an existing building, t_1 is the year of demolishing an existing building, t_1' is the year of demolishing an existing building after refurbishment, t_2 is the year of demolishing a new building, $I_C^{(exi)}$ is the impacts (both GHG emissions, costs, and material footprints) of constructing an existing building, $I_D^{(exi)}$ is the impact of demolishing an existing building, $I_C^{(new)}$ is the impact of constructing a new building, $I_D^{(new)}$ is the impact of demolishing a new building, $I_R^{(exi)}$ is the impact of production, installation, EoL treatment of the PCE-refurb, $I_{O(an)}^{(new)}$ is the impact of operating a new building per year, $I_{O(an)}^{(exi)}$ is the impact of operating an existing building, and $I_{O(an)}^{(ren)}$ is the impact of operating a refurbished existing building per year.

6.2.5 Up-scaling both actual and annualized values at a country level

Eq. (1) and Eq. (2) indicate how the life cycle environmental and economic impacts of construction, refurbishment, operation, and demolition activities at the product level. The yielded actual values and annualized values were further up-scaled by combining them with building stock information. The up-scaled actual-value impacts of in year *t* in the BAU, REB, and REN scenarios are estimated using Eq. (3). The up-scaled annualized-value impacts in year *t* in the BAU, REB, and REN scenarios are formulated as Eq. (4).

$$Actual\ country-level\ impacts = \begin{cases} \sum_{V=1}^{V=5} S_{(BAU,V)}(t) I_{O(an)}^{(BAU,V)} + F_C(t) I_C^{(new)} + F_D(t) I_D^{(exi)}, & BAU \\ \sum_{V=1}^{V=5} S_{(REB,V)}(t) I_{O(an)}^{(REB,V)} + (F_C(t)+F_R(t)) I_C^{(new)} + (F_D(t)+F_R(t)) I_D^{(exi)}, & REB \\ \sum_{V=1}^{V=5} S_{(REF,V)}(t) I_{O(an)}^{(REF,V)} + F_C(t) I_C^{(new)} + I_R^{(exi)} F_R(t) + F_D(t) I_D^{(exi)}, & REN \end{cases} \quad (3)$$

$$Annualised\ country-level\ impacts =$$

$$\begin{cases} \sum_{V=1}^{V=5} S_{(BAU,V)}(t) I_{O(an)}^{(BAU,V)} + \sum_{V=1}^{V=4} S_{(BAU,V)}(t) \frac{(I_C^{(exi)}+I_D^{(exi)})}{t_1-t_0} + \sum_{2015}^{t} F_C(t) \frac{I_C^{(new)}+I_D^{(new)}}{t_2-t}, & BAU \\ \sum_{V=1}^{V=5} S_{(REB,V)}(t) I_{O(an)}^{(REB,V)} + \sum_{2015}^{t} (F_R(t)+F_C(t)) \frac{I_C^{(new)}+I_D^{(new)}}{t_2-t} + \sum_{V=1}^{V=4} S_{(REB,V)} \frac{I_C^{(exi)}+I_D^{(exi)}}{t-t_0}, & REB \\ \sum_{V=1}^{V=5} S_{(REN,V)}(t) I_{O(an)}^{(REN,V)} + \sum_{2015}^{t} F_R(t) \frac{I_R^{(exi)}}{(t_1'-t)} + F_C(t) \frac{I_D^{(new)}}{t_2-t} + \sum_{V=1}^{V=4} S_{(REN,V)}(t) \frac{(I_C^{(exi)}+I_D^{(exi)})}{t_1-t_0} + \sum_{2015}^{t} F_R(t) \frac{I_C^{(exi)}+I_D^{(exi)}}{t_1'-t_0}, & REN \end{cases} \quad (4)$$

where v (=1,2,3,4,5) represents five vintage cohorts of houses in the Netherlands (up to 1960, 1961–1980, 1981–2000, 2001–2014, 2014-2050), $I_{O(an)}^{(BAU,V)}, I_{O(an)}^{(REB,V)}, I_{O(an)}^{(REN,V)}$ are operation impacts of a house in vintage cohort *v* in different scenarios, $F_R(t)$ is refurbished/rebuilt floor area in year *t*, $F_C(t)$ is newly constructed floor area in year *t*, $F_D(t)$ is demolition floor area in year *t*, $S_{(BAU,V)}(t), S_{(REB,V)}(t),$ and $S_{(REF,V)}(t)$ are housing stocks of vintage cohorts *v* in year *t* in different scenarios.

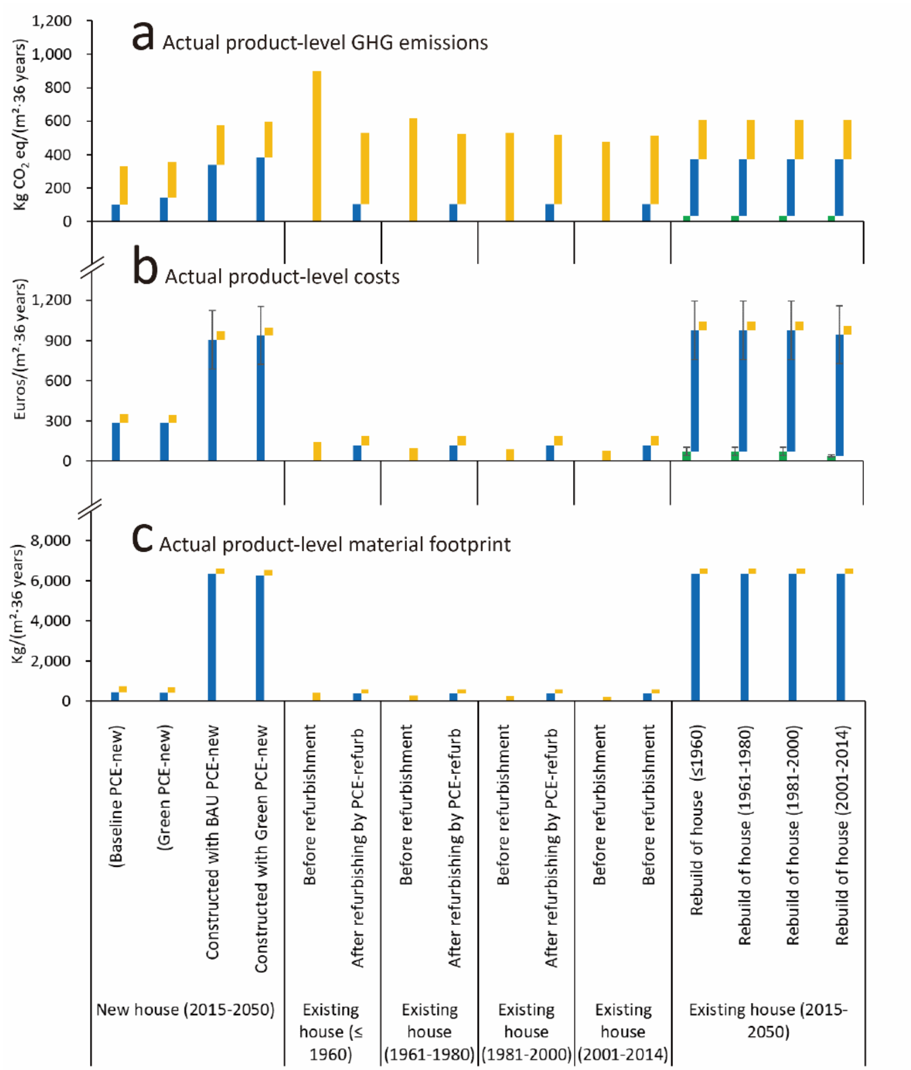
6.3 Results

6.3.1 Product-level GHG emissions, costs, and material footprints

The actual-value and annualized-value GHG emissions, costs, and material footprints of each system are presented in Figure 6.4. The temporal scale of the actual-value approach is 2015-2050. Results of actual-value and annualized-value approaches are analogous to some degree but also could lead to different conclusions. The green PCE-new system does not show an apparent economic and environmental advantage over the baseline PCE-new system, using both actual-value and annualized-value modeling.

The GHG mitigation, cost saving, and material footprint reduction of green PCE-refurb are more significant than those of the green PCE-new. However, the performance of the PCE-refurb system is highly dependent on the vintage of the building that is to be refurbished. Implementing PCE-refurb in buildings constructed before 1960 leads to significant GHG mitigations, cost savings, and resource use reductions. These benefits decrease if the building is in a newer cohort. From the economic point of view, the green PCE-refurb solution is costlier than walls without refurbishment using an actual-value approach but shows lower life cycle costs using an actual-value approach. This is because reuse is expected to yield considerable financial benefits using an actual-value approach.

In addition, rebuild of house emits more GHG than refurbishment using an actual-value approach whereas has lower life cycle GHG emissions using an annualized-value approach. However, rebuilding is significantly costly and resource-intensive in both actual-value and annualized approaches, therefore, not economically and material-efficiently feasible.


a Actual product-level GHG emissions
Kg CO_2 eq/(m²·36 years)
1,200
1,000
800
600
400
200
0
b Actual product-level costs
Euros/(m²·36 years)
1,200
900
600
300
0
c Actual product-level material footprint
Kg/(m²·36 years)
8,000
6,000
4,000
2,000
0
(Baseline PCE-new)
(Green PCE-new)
Constructed with BAU PCE-new
Constructed with Green PCE-new
Before refurbishment
After refurbishing by PCE-refurb
Before refurbishment
After refurbishing by PCE-refurb
Before refurbishment
After refurbishing by PCE-refurb
Before refurbishment
Before refurbishment
Rebuild of house (≤1960)
Rebuild of house (1961-1980)
Rebuild of house (1981-2000)
Rebuild of house (2001-2014)
New house (2015-2050)
Existing house (≤ 1960)
Existing house (1961-1980)
Existing house (1981-2000)
Existing house (2001-2014)
Existing house (2015-2050)

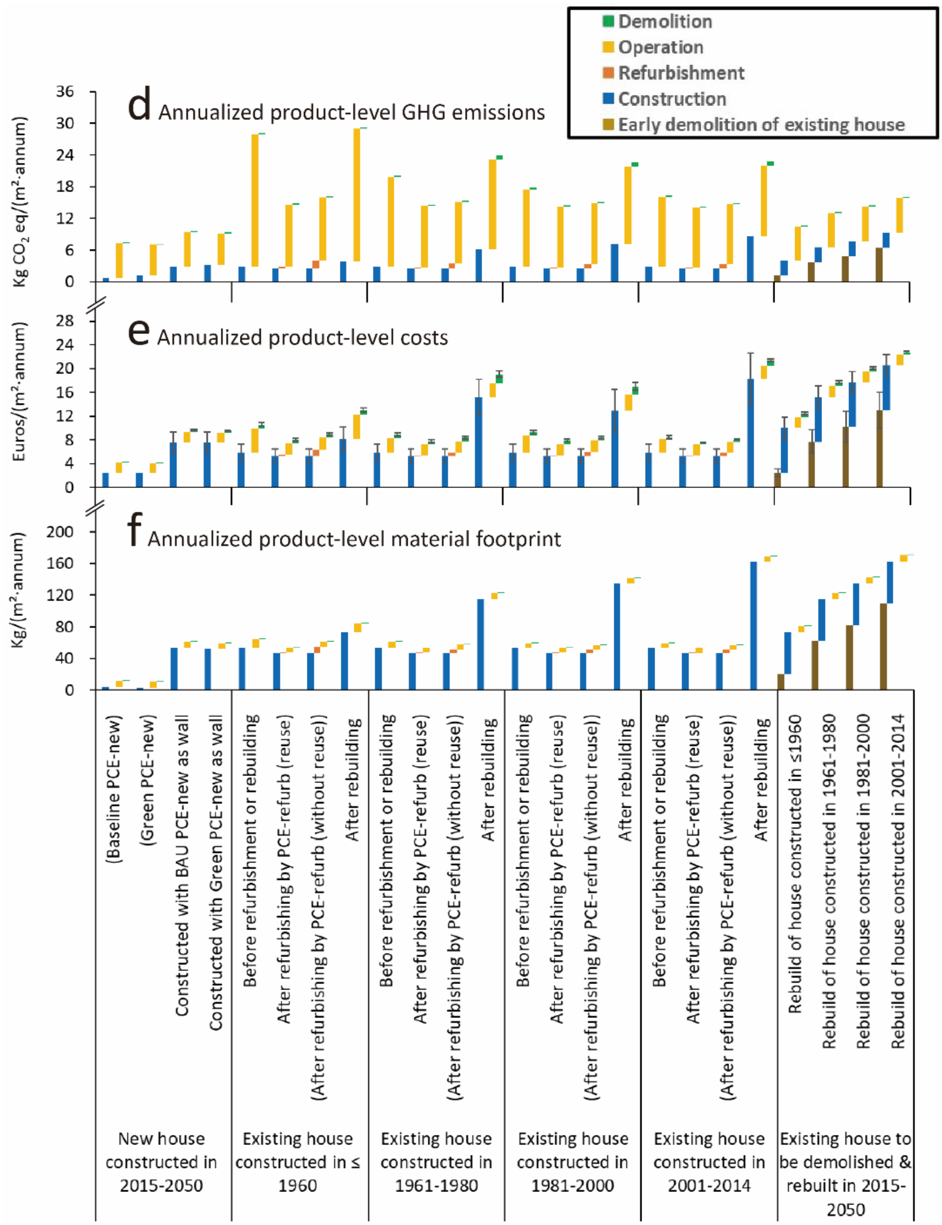


Figure 6.4 Actual-value (a) GHG emissions, (b) life cycle costs, and (c) life cycle material footprints and annualized-value (d) GHG emissions, (e) life cycle costs, and (f) life cycle material footprints of each technological system. Note: At a product level, GHG emissions, costs, and material footprints from cooking, hot water supply, electric appliance use, and lighting were not included. The electricity mix remains at the 2015 level for the period 2015–2050. The operation impacts of the actual-value

approach in (a)-(c) were accounted for the period 2015-2050. The "early demolition of existing house" in Panel (d)-(f) is the difference between "before refurbishment and rebuilding" and "after rebuilding". The "36 years" mean the time span from 2015 to 2050.

6.3.2 Dynamics of building stock and material requirements

Based on the dynamic MFA model, we investigated the inflow and outflow of the stock per annum, turnover of the stock, and material use from 2015 to 2050 as shown in Figure 6.5. Building stocks, inflows and outflows, and material use were modeled at the end of the discrete-time interval. The BAU and REN scenarios have the same construction and demolition floor area per year, based on the expected end-of-life of houses in the existing building stock of 2015. In the REN scenario, the annual floor area that is renovated is 16.95 million m^2, amounting to 593.10 million m^2 in total. The REB scenario has far more construction and demolition floor areas owing to extensive reconstruction. In the REB scenario, 16.95 million m^2 of old buildings are demolished and then rebuilt as opposed to being renovated. However, three scenarios have an identical gross habitable surface per year, as shown in panels d, e, and f of Figure 6.5. Panels g, h, and i of Figure 6.5 show the main materials used in the three scenarios. The material use in the REN scenario was slightly higher than that in the BAU scenario. The material use in the REB scenario was approximately two times more than that in the BAU and REN scenarios. Details of the dynamic MFA model are presented in the SI.

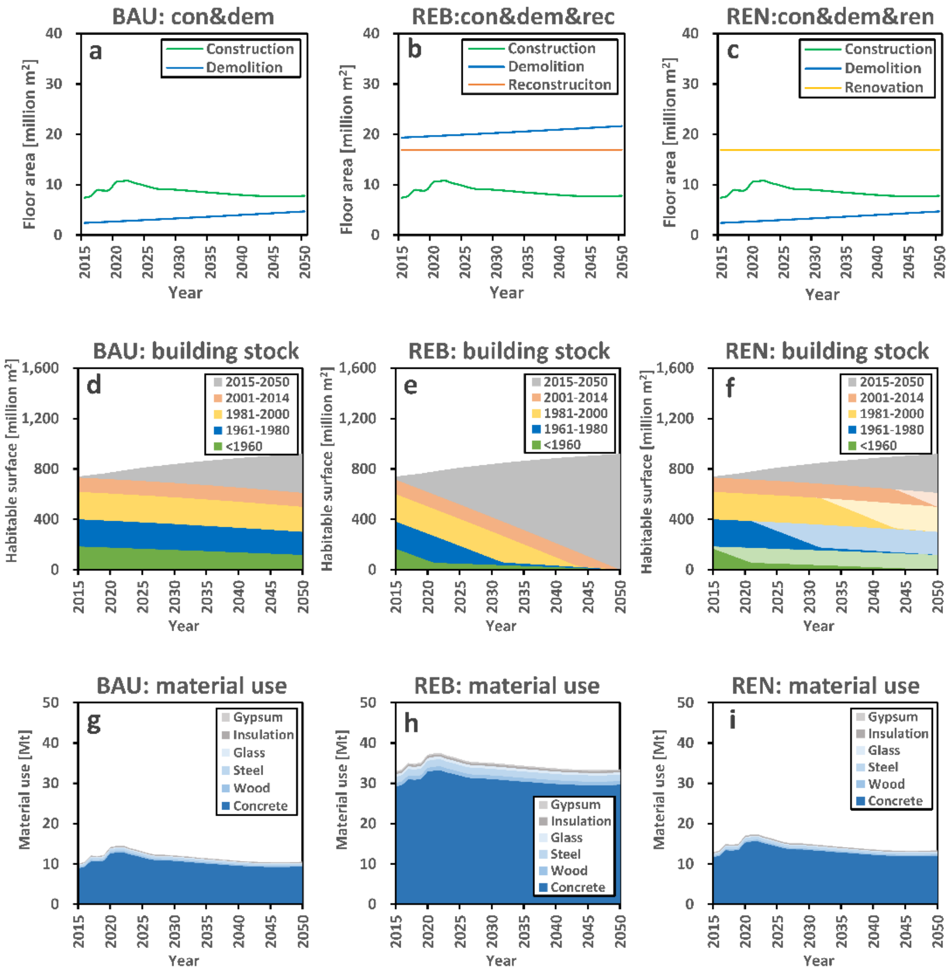


Figure 6.5 Dynamics of construction, demolition, and renovation floor area and residential building stocks of three scenarios for 2015–2050. The slightly lighter-colored areas in each construction cohort area in panel (f) represent refurbished building stocks. “Material use” in panels (g)-(i) does not mean primary raw material use but the use of products.

6.3.3 Country-level GHG emissions, costs, and material footprints

The environmental and economic information from the LCA and LCC are scaled up to the total flooring area in the Netherlands by combining them with stock information from the building stock model. We compared the 2015 electricity mix with a dynamic electricity mix with an increasing share of renewables up to 2050, in each scenario. The share of renewable sources is 10% in 2015 and will increase to 50% in 2030 (EZK 2015) and 100% in 2050 (EZK 2019). The up-scaled actual-value and annualized-value life cycle of GHG emissions, costs, and material footprints for the BAU, REB, and REN scenarios are shown in Figure 6.6. Details of the renewable electricity modeling are presented in the SI.

Our actual-value approach (Figure 6.6a) shows a clear trade-off between embodied emissions and operational emissions. Owing to additional material use, the REB and REN scenarios had higher emissions in 2015, compared with the BAU scenario. These embodied emissions from the REN scenario are paid back by 2027, after which there is a net environmental benefit. The REB scenario emits much more GHG emissions compared to the BAU, and cannot compensate for the increased embodied emissions during the modeled time. This is because heat pumps and other appliances using grey electricity cannot create gains over efficient gas boilers. However, this situation is reversed when the development of renewable electricity is considered. The payback periods of the REN scenario remain the same. The REB scenarios can return in 2038 and will yield less GHG emissions than the REN scenario from 2039 onwards. From an economic perspective, although the REN scenario has much lower life cycle costs than the REB scenario, both REB and REN cannot reduce costs compared to the BAU scenario (see Figure 6.6b). Material footprints of three scenarios (Figure 6.6c) present the same trend as the cost results. However, it is noteworthy that the supply of cleaner electricity considerably reduces GHG emissions but slightly mitigates the material footprints.

The annualized-value approach provides additional insights compared to the actual-value approach. With this approach, the REB scenario shows a similar emission tendency compared to the BAU scenario if the electricity mix remains steady (see Figure 6.6d). Emissions from the REN scenario will be noticeably less than that of the other two scenarios. Considering the development of renewable electricity, the emissions of the three scenarios would be reduced to different extents, most significantly for the REB scenario. From an economic perspective, the REN scenario can save expenses to some degree compared with the BAU scenario (Figure 6.6e). However, the REB scenario is more expensive and not a cost-effective option. From the material footprint perspective, the REB scenario requires noticeably more primary materials than the other two scenarios (Figure 6.6f). The REN scenario has lower material footprints compared to with BAU scenario using an annualized-value approach. Note that material footprints of the REB and REN scenarios (Figure 6.6f) both show a descending trend, which does not indicate that construction and renovation activities in the future are less material-intensive. For the REB scenario, the decreasing material footprints result from additional demolition of existing houses, which leads to a cessation of the annualized construction and demolition material use of existing houses. While as for the REN scenario, it is because that refurbishment reduced the annualized construction and demolition material use of existing houses.

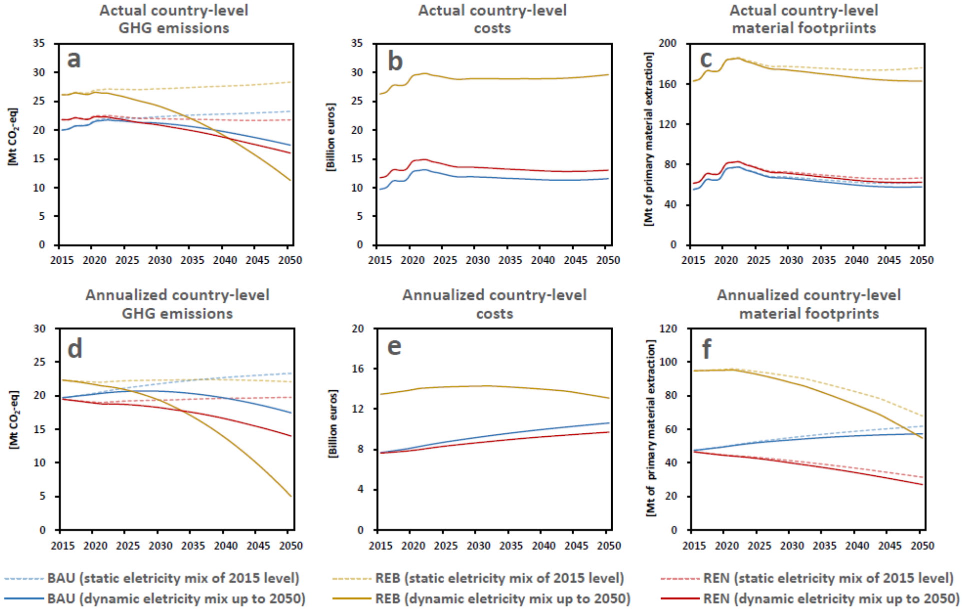


Figure 6.6 (a-c) Actual and (d-f) annualized country-level GHG emissions in [kg CO_2 eq], costs in [billion euros], and material footprints in [Mt of primary material extraction] of the housing sector in the Netherlands for 2015–2050. Note: impacts of cooking, hot water supply, electric appliance use, and lighting were included. It is assumed the costs of electricity and gas remain steady-state of the 2015 level.

6.3.4 Circularity goal: halving material footprint by 2030 and achieving full circularity by 2050

For the 2030 circularity goal, the 50% reduction in material footprints can be measured either in general or for each resource individually (Potting et al. 2018; Bastein et al. 2017). We measured the material footprints in general as shown in Figure 6.7a. None of the three scenarios can reduce the overall material footprint. Given that building stock undergoing an extensive energy renovation, the Netherlands is less likely to achieve the circularity goal by 2030, even with advanced recycling systems in place.

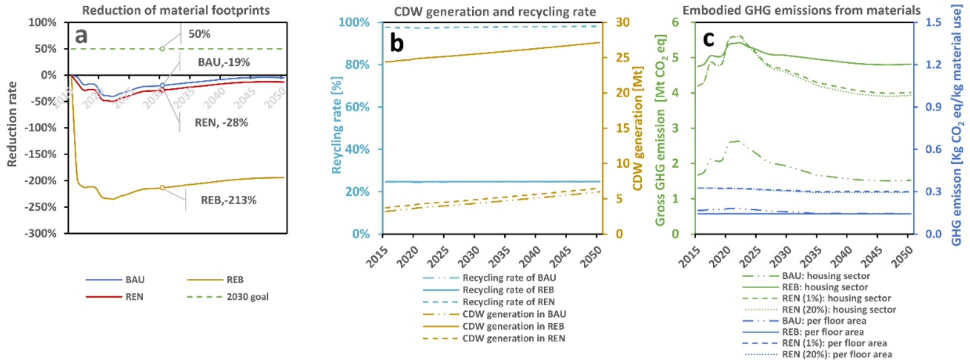


Figure 6.7 (a) Reduction rate of material footprints of three scenarios compared with 2015 level of the BAU scenario, (b) the generation of construction and demolition waste and recycling rate of three scenarios, (c) embodied GHG emissions of material uses of three scenarios. Note: The "(1%)" in (c) represents the light-weight concrete waste accounts for 1% in the gross normal-weight concrete waste from 2015 to 2050; the "(20%)" indicates the share of the light-weight concrete waste linearly increases from 1% in 2015 to 20% in 2050.

Figure 6.7b shows the waste generations and recycling rates of three scenarios. Owing to intensive demolition and reconstruction, the REB scenario has a relatively large amount of CDW generation compared to the other two scenarios. The recycling rates of the BAU and REB scenarios remain stable at approximately 25% till 2050 if no additional efforts to upgrade the current CDW treatment system are undertaken. These scenarios assume a recycling rate of concrete waste less than 5%. The REN scenario has a significantly higher recycling rate, approximately 98% because the ADR and HAS technological systems can fully recycle concrete waste.

Figure 6.7c shows the embodied GHG emissions associated with materials in the three scenarios. For each scenario, the gross embodied GHG emissions account for both materials for PCE and also other materials used for constructing new buildings. The gross GHG emissions from material use show an ascending trend until 2023 and then a long continuous descending trend. This relates to vast construction activities in the period from 2017-2037, as shown in Panel a, b, and c of Figure 6.5. The REN scenario generally has lower GHG emissions than the REB scenario, but is over two times higher than that of the BAU scenario. When the share of lightweight concrete waste remains steady at 1% of gross concrete waste, the secondary materials are not sufficient for the production of green PCE-refurb. The deficit was assumed substituted by virgin raw materials. When the share increase to 20% in 2050, the GHG emissions of the REN scenario would just be slightly reduced. We further investigated the GHG emissions per kg material use of three scenarios by dividing the gross GHG emissions by gross material uses (see Panel g, h, and i of Figure 6.5). As shown in Figure 6.7c, the carbon footprint per kg material use of the REN scenario is twice that of the REB and BAU scenarios. This is because concrete is the primary material for rebuilding, and energy renovation depends heavily on synthetic insulation materials such as expanded polystyrene and aerogel that have a higher carbon footprint compared to concrete.

6.3.5 Decarbonization goal: reduction of 49% GHG emissions by 2030 and 95% by 2050

In this section, we evaluated whether the three scenarios BAU, REB, and REN can achieve the interim and long-term decarbonization goals. The effects of adopting green electricity and applying different insulation levels are assessed. The energy mix for electricity production in the Netherlands over time was presented in Figure 6.8a. The share of renewable sources is 10% in 2015 and will increase to 50% in 2030 (EZK 2015), and will achieve 100% renewable electricity production by 2050 (EZK 2019).

We additionally added two scenarios in which the thermal insulation performance of new houses meets the insulation requirement of nZEB. The “BAU/REB/REN-a” scenario represents the insulation level of the new houses in those scenarios that meet the nZEB. insulation requirement from the ZEBRA2020 database (2020). The “BAU/REB/REN-b” denotes the insulation level of the new houses in those scenarios that meet the nZEB insulation requirement from the TABULA database (2017). Figure 6.8b shows the historical and prospective emissions from the residential sector of the three previously defined scenarios and six additional scenarios. For BAU-related scenarios, without renovation and reconstruction and with the implementation of high-insulation facades and electrical appliances for new buildings, the residential sector would be unable to achieve the carbon-neutral goal in 2030 and 2050. The three REN scenarios have the potential to fulfil the decarbonization goal by 2030 but fail to reach a carbon-neutral level by 2050. Only the REB scenario appears suitable for achieving both mid-term and long-term goals.

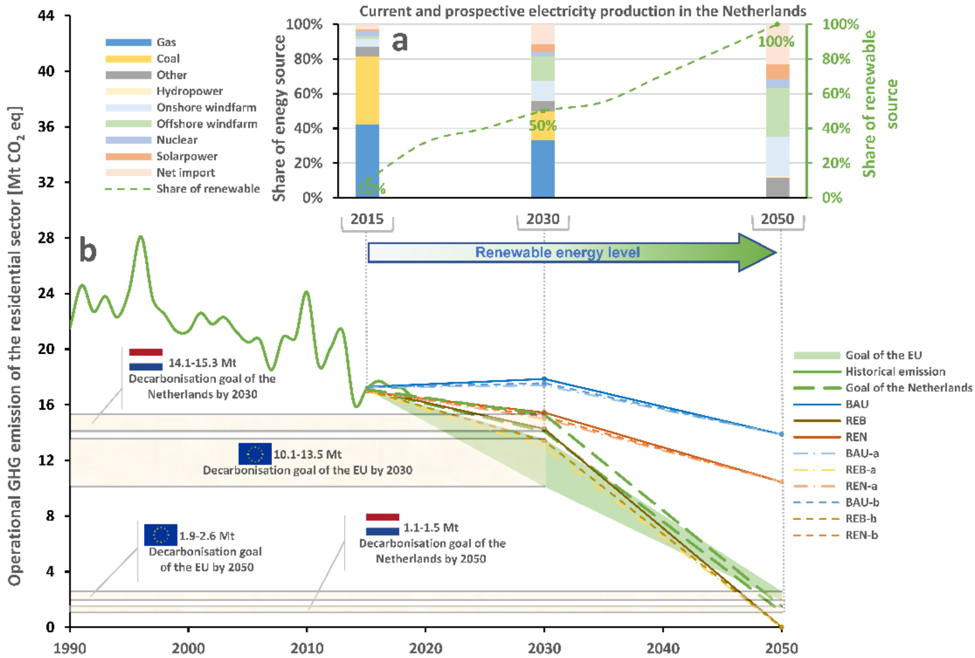


Figure 6.8 (a) Current and prospective electricity production and (b) greenhouse gas emission of the residential sector in the Netherlands. Note: Only operational emissions were considered. The "BAU/REB/REN-a" represents the insulation level of the new houses that meet the nearly zero energy building (nZEB) insulation requirement from the ZEBRA2020 database (2020). The "BAU/REB/REN-b" denotes the insulation level of the new houses that meet the nZEB insulation requirement from the TABULA database (2017).

6.4 Discussion

The discussion section mainly focuses on the application of the actual-value and annualized-value modeling, the challenges and opportunities in realizing the circularity and decarbonization goals of the built environment. First, we expressed the results of LCA and LCA. This results from the mismatch of temporality between LCA/LCC and MFA, as shown in Figure 6.9. Synchronic life cycle time was assumed in the LCA and LCC (120 years), while in MFA an exact diachronic time of 2015-2050 was explored. Therefore, under the temporal scope of the MFA, circularity interventions, such as building lifetime extension, recycling, and reuse of materials that occur after 2050, cannot be included. To overcome this drawback, an annualized-value approach was introduced to take into account the benefits from PCE reuse and building lifetime extension.

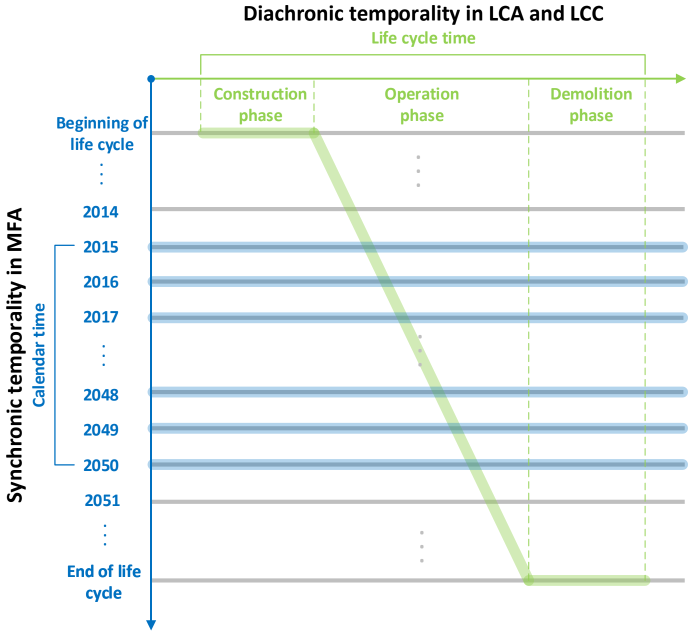


Figure 6.9 Temporality in material flow analysis, and life cycle assessment/life cycle costing. Modified based on the research (Birat 2015).

It is noteworthy that the selection of different estimation approaches led to different conclusions. The annualized-value approach is more capable of theoretical comparison as it can take into account the sunken costs and future benefits; while the actual-value approach better reflects real situations. The annualized-value approach shows that the REN scenario leads to lower GHG emissions, costs, and material footprint compared to the BAU scenario. The REB scenario shows a greater GHG mitigation potential than the other two scenarios but also leads to higher costs and material footprint, using the annualized-value approach. The actual-value approach reveals a clearer trade-off between GHG emission and capital investment and between energy use and material depletion in energy renovation. Therefore, the essence of energy renovation (especially deep renovation) is to sacrifice capital investment and material for lower GHG emissions and energy use. Moreover, combining use of actual-value and annualized-value approaches can provide comprehensive insights that help policymakers, for instance, in assessing how the use of carbon budgets and cost-effective strategies evolves over time.

In our assessment of the 2030 circularity goal, reduction of material footprints was achieved through recycling, lightweight design such as using lightweight concrete and aerogel in green PCE-refurb, and using renewable energy carriers. However, lightweight design was only applied to the green PCE-refurb whereas will lead to a more noticeably less use of material if implemented on new buildings. For example, by applying lightweight design in all steel and aluminum products, the material required can be reduced by up to 30% (Carruth et al. 2011). These factors induced the overestimation of material footprints. Note that we did not consider the development of cleaner electricity in the manufacturing sector as operational energy use dominates the life cycle energy use of a building.

For the 2050 circularity goal, our results imply that the REN scenario has the potential to boost the recycling rate to almost 100%, but unfortunately, we also find this scenario brings with it more embodied GHG than the BAU scenario. In the REN scenario, green aerogel is extensively used in green PCEs. However, the technological maturity of the aerogel is still at a lab scale, production per unit of aerogel needs a large amount of grey electricity and raw materials compared with producing per unit of baseline insulation expanded polystyrene. Thus, the primary focus of future innovation in the PCE system should be a cleaner production process for green aerogel. In addition, secondary materials yielded from the ADR, HAS, and DGR technological systems have relatively lower life cycle environmental impacts compared to virgin material, although we note that these results are highly sensitive to choices in allocation method and impact category (Zhang et al. 2019a, 2020a). Currently, these recycling systems still rely on diesel to operate. At a commercialized scale, fossil fuels will have to be replaced by cleaner energy sources.

Evaluation of the decarbonization goals reveals the roadmap towards a low-carbon and energy-efficient built environment. With regard to the passive approach, improving the insulation of building elements in the REN proved to prevent heat loss compared to the BAU scenario. The thermal transmittance of new building elements (walls, floors, glazing, roofs) in the REN is higher than the requirement of nZEB for houses in the Netherlands. This is because the PCE-refurb is specific for implementation in cold zones such as the Netherlands, while the PCE-new system is currently designed for all climatic areas in the EU. Therefore, the insulating performance of the PCE-new should be further specified in cold, cool, and warm zones. Conversely, although the thermal insulation level of the façade in the nZEB requirement is superior to the baseline and green PCE-new, the BAU/REB/REN-a and -b scenarios still cannot noticeably reduce GHG emissions compared with the BAU/REB/REN scenarios. As of the active approach, the use of renewable energy is a crucial factor affecting the decarbonization of the residential sector. Refurbishment by the PCE system can realize the interim goal of carbon mitigation of 49% by 2030 but cannot further support the realization of the long-term goal. A nearly net-zero goal by 2050 can be achieved if nationwide reconstruction is implemented. Reconstruction intervention is theoretically feasible. However, it reflects a crucial point that implementing energy renovation only by a passive approach, such as refurbishment with PCE-refurb, is insufficient to achieve the long-term decarbonization goal. The replacement of traditional gas-based systems (such as boilers, water heaters, and gas stoves) with electricity-based systems and the supply of 100% renewable electricity are two decisive conditions for shifting to a carbon-neutral society.

6.5 Conclusions

Regarding the issues of energy inefficiency and the surging volumes of CDW in Europe, the PCE system delivers an energy-efficient improvement in new building construction and existing building renovation by high-value recycling CDW as secondary raw material in the production of PCE-new and PCE-refurb. Our assessment integrated a top-down, stock-driven building stock model with LCA and LCC to explore the product-level and up-scaled performance of the proposed PCE solutions for new building construction and existing building renovation in the Netherlands from 2015 to 2050. Three scenarios, BAU, REB, and REN, were established. The BAU scenario does not apply a baseline PCE-new or include any renovation strategies for old buildings. The REN scenario implements the green PCE-new and green PCE-refurb system for material-efficient energy renovation. The REB scenario demolishes and rebuilds old buildings instead of renovating them. The building stock model was used to simulate the construction, demolition, renovation floor area per annum, and stock cohorts of the three scenarios. The LCA and LCC were deployed to estimate the life cycle environmental and economic impacts of the proposed PCE system, as well as building reconstruction. The results of the LCC and LCA were up-scaled using the stock and flow information from the dynamic building stock model.

The product-level and up-scaled results were expressed as both actual values and annualized values. The annualized-value approach is more capable of theoretical comparison, while the actual-value approach better reflects real situations. The selection of different estimation approaches led to different conclusions. The actual-value approach revealed the trade-offs between GHG emissions and investment/material use in energy renovation. However, the annualized-value approach proved the PCE system achieved comprehensive benefits compared to the BAU scenario.

We further evaluated the extent to which the circularity and decarbonization goals can be realized by up-scaling the proposed PCE system to the residential building sector. The Netherlands aims to achieve a reduction of 50% material footprints by 2030 compared to the 2015 level. The results show the BAU and REN scenarios cannot reduce resource uses till 2050. Regarding the circularity goal by 2050, advanced technological systems in the REN scenario can raise the recycling rate from the current 25% to 98%. However, the associated embodied emissions of the REN scenario is twice that of the BAU scenario, due to the use of carbon intensive aerogels as insulation. Therefore, the Netherlands is less likely to achieve the circularity goal by 2030 and 2050 with the proposed PCE system, unless a cleaner production process for aerogel is in place. It should be noted that we did not consider the development of renewable electricity for manufacturing processes in the study.

Furthermore, operational GHG emissions of the residential building stock in 2030 and 2050 were quantified under different scenarios. We found that if no energy renovation strategies are applied, the baseline BAU scenario cannot achieve the decarbonization goal by 2030 or 2050. REN implementing the PCE system for extensive energy renovation can achieve an interim goal of 49% carbon mitigation by 2030 but still cannot realize the carbon-neutral level by 2050. Only our REB scenario, in which traditional gas-based heating systems are replaced with electricity-based systems and supplied with renewable electricity, can reach the long-term carbon goals.

Acknowledgements

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Appendix

Table A6.1 Material intensity for new houses (2015-2050) in the Netherlands. Note: As for new houses that are constructed after 2015, Arnoldussen et al. (2020) reported the material intensity for constructing 1 m^2 of a new detached house, semi-detached house, terraced house, maisonette, and apartment in the Netherlands. Concrete accounts for more than 80% of material use by weight in new buildings. Since "other" fraction makes up around 1% of the gross material requirement, its GHG emissions were not considered. Regarding the material intensity of existing houses that were constructed from 1900 to 2014, we assumed it is the same as the material intensity of new houses (Zhang et al. 2020b).

Building type	Share of house	Material intensity [Kg/m^2]	Concrete [Kg/m^2]	Wood [Kg/m^2]	Steel [Kg/m^2]	Glass [Kg/m^2]	Insulation [Kg/m^2]	Gypsum [Kg/m^2]	Other [Kg/m^2]
Detached house	15.98%	1,200	1,048.60	42.06	33.64	23.83	19.63	19.63	12.62
Semi-detached house	11.39%	1,430	1,238.99	53.35	51.62	25.81	18.93	27.53	13.77
Terraced house	33.60%	1,120	965.01	51.22	40.43	25.61	17.52	8.09	12.13
Apartment and maisonette	39.03%	1,630	1,449.12	16.83	96.75	25.24	18.93	8.41	14.72

Table A6.2 Weighted material intensities (in Table A6.1) and their GHG emission indicators

Mateiral	Weighted material intensity [Kg/m^2]	Emission indicator [kg CO_2 eq/kg]	Reference process in Ecoinvent 3.4
Concrete	1198.52	0.14791	BAU siliceous concrete production
Wood	36.57	-1.68752	"planing, board, softwood, u=20%-GLO"
Steel	62.60	2.41765	"steel production, converter, low-alloyed-ReR"
Glass	25.20	0.99312	"flat glass production, uncoated-GLO"
Insulation	18.57	0.69539	"polystyrene foam slab production, 100% recycled | polystyrene foam slab | Cutoff, U – RoW"
Gypsum	12.27	0.01063	"gypsum production, mineral | gypsum, mineral | Cutoff, U-GLO"

Table A6.3 GHG emission indicators for construction and demolition of houses. Note: materials account for around 90% of gross carbon emission in the construction stage of a building, in contrast to manpower, energy and equipment around 8%, 1% and 0.1% (Shao et al. 2014). Therefore, it was assumed the emission of manpower, energy and equipment account for 10% of the material emission. The carbon emission at the demolition stage is deemed equal to 10% of the construction stage (Lu and Wang 2019).

	Construction emission (kg CO_2 eq/m^2)		Demolition(kg CO_2 eq/m^2)
	Material	Energy and equipment	
Emission indicator	304.98	33.89	33.89

Table A6.4 Construction costs of different types of new houses after 2015 in the Netherlands [€/m²] (Arcadis 2017)

Building type	Share of housing	Lowest level	Highest level	Average level
Detached house	15.98%	600	1,175	888
Semi-detached house	11.39%	650	1,080	865
Terraced house	33.60%	600	800	700
Apartment and maisonette	39.03%	810	1,385	1,098

Table A6.5 Price index of house construction costs for the period 1995 to 2020 (CBS 2021a).Note: Due to lack of data, we simplified the estimation of the construction costs for existing houses from 1900 to 2014 by using the average house price of the period 1995 to 2014. This may result in overestimation as prices of an old house are lower. However, we also noticed from the reports that the real house prices in the Netherlands did not dramatically adjust from 1965 to 1995 (Vries 2010). The estimated construction costs of houses from 1900 to 2014 is 711.60 €/m² with an uncertainty range of (541.20, 881.56).

Years	Price index of house construction costs	Estimated construction costs [€/m²]
1995	90.1	558.37
1996	90.7	562.09
1997	92.4	572.63
1998	94.9	588.12
1999	96.5	598.04
2000	100.0	619.73
2001	105.2	651.95
2002	109.3	677.36
2003	111.5	690.99
2004	113.7	704.63
2005	115.9	718.26
2006	119.3	739.33
2007	124.1	769.08
2008	129.8	804.40
2009	130.0	805.64
2010	130.8	810.60
2011	133.4	826.71
2012	135.7	840.97
2013	136.0	842.83
2014	137.2	850.26
2015	139.8	866.38

2016	142.6	883.73
2017	145.9	904.18
2018	149.6	927.11
2019	153.8	953.14
2020	157.3	974.83

Table A6.6 Demolition costs of buildings in the Netherlands [euro/m^2](Arcadis 2017). Note: the mean value of those costs is selected to estimate the costs of demolition of old houses. The Netherlands in 1993 and the EU in 2005 banned the use of asbestine materials in construction (Government of the Netherlands 2020), the asbestos is only included in the demolition waste of old buildings. Hence, we assumed demolition costs of buildings that were constructed before 2000 needs to consider costs for asbestos removal. The average demolition costs of buildings constructed after 2000 is 39.50 euro/m^2 with an uncertainty range of (31.00, 48.00); buildings constructed before 2001 is 72.00 euro/m^2 with an uncertainty range of (40.00, 104.00).

	Lowest level	Highest level
Demolition costs for small scale project	31.00	38.00
Demolition costs for large scale project	36.00	48.00
Costs for asbestos removal	9.00	56.00

Table A6.7 Thermal transmittance [W/(m ²·K)] of each building element. Note: assumptions based on TABULA database (TABULA 2017); b data from BPIE report (Economidou 2011); c calculated results based on ISO 6946 (ISO 2017b); d data from ZEBRA2020 database (2020); e data from the TABULA database from the EPISCOPE project (TABULA 2017).

Element	Existing building	Existing building with PCE-refurb	New building with PCE-new	nZEB-ZEBRA-NL [d]	nZEB-EPISCOPE - NL [e]	nZEB-EPISCOPE for EU Member States [e]
Floor	3.370 [a]	3.370 [a]	0.181[a]	0.130	0.110	0.060-0.320
Roof	0.520 [a]	0.520 [a]	0.118 [a]	0.110	0.080	0.060-0.480
Window	1.300 [a]	1.300 [a]	1.300 [a]	0.780	1.000	0.500-2.800
Wall in general	/	/	/	0.110	0.100	0.090-0.480
Wall (≤ 1960)	2.700 [b]	0.203 [c]	/			/
Wall (1961-1980)	1.000 [b]	0.180 [c]	/	/	/	/
Wall (1981-2000)	0.600 [b]	0.161 [c]	/	/	/	/

Wall (2001-2014)	0.400 [b]	0.142 [c]	/	/	/	/
Wall-baseline PCE-new(≥2015)	/	/	0.317 [a]	/	/	/
Wall-green PCE-new(≥2015)	/	/	0.190 [a]	/	/	

Table A6.8 Energy demand per annum for space heating and cooling of different envelope systems. Note: According to Norm DIN V 18599(DIN 2011) for split air conditioning (>12kW), the seasonal energy efficiency ratio is around 4.7. This indicated that 4.7 kWh of cooling is supplied with 1 kWh of electricity.

House	Heating demand [kWh/(m^2·annum)]	Cooling demand [kWh/(m^2·annum)]	Electricity used for cooling [kWh/(m^2·annum)]
Existing house (≤1960)	99.80	1.31	0.28
Existing house (1961-1980)	67.74	1.40	0.30
Existing house (1981-2000)	58.03	1.64	0.35
Existing house (2001-2014)	52.17	1.85	0.39
Existing house (≤1960) refurbished with PCE-refurb	46.68	2.29	0.49
Existing house (1961-1980) refurbished with PCE-refurb	45.85	2.07	0.44
Existing house (1981-2000) refurbished with PCE-refurb	45.26	2.07	0.44
Existing house (2001-2014) refurbished with PCE-refurb	44.67	2.08	0.44
New house (≥2015) with baseline PCE-new	29.25	3.35	0.71
New house (≥2015) with green PEC-new (≥2015)	25.90	3.84	0.82

Table A6.9 Reference processes for the production of primary and secondary material

Primary material	Remark and sources
Concrete	Foreground process "BAU normal-weight siliceous concrete production"
wood	"planing, board, softwood, u=20% | sawnwood, board, softwood, dried (u=20%), planed | Cutoff, U-RoW"
Steel	"steel production, converter, low-alloyed | steel, low-alloyed | Cutoff, U-RER"
Glass	"flat glass production, uncoated | flat glass, uncoated | Cutoff, U-RER"
Insulation-EPS	To use EPS to represent the insulating material in a new building: "polystyrene foam slab production, 100% recycled | polystyrene foam slab | Cutoff, U - RoW"
Insulation-aerogel	Foreground process "green aerogel production"
Gypsum	"market for gypsum, mineral | gypsum, mineral | Cutoff, U-GLO"
Secondary material	**Remark and sources**
BAU recycled concrete	The secondary coarse aggregate was reproduced by the wet recycling process (Zhang et al. 2019a) to replace the primary coarse gravel in "BAU normal-weight siliceous concrete production".
VEEP green concrete	Foreground process "VEEP normal-weight siliceous concrete production", "VEEP lightweight concrete production"
Wood	"planing, board, softwood, u=20% | sawnwood, board, softwood, dried (u=20%), planed | Cutoff, U-RoW"
steel	"steel production, electric, low-alloyed | steel, low-alloyed | Cutoff, U-RER"
Glass	to use the secondary silica sand recycled by DGR system to replace the primary sand in process "flat glass production, uncoated | flat glass, uncoated | Cutoff, U-RER"
Insulation-EPS	The recycling process for EPS is currently unknown, to use the impact of primary EPS to replace secondary EPS.
Insulation-aerogel	The recycling process for aerogel is currently unknown, to use the impact of primary aerogel to replace secondary aerogel.

Table A6.10 Share of source for electricity production in 2015 in the Netherlands. Note: the energy mix of electricity production in 2015 is referred to the process "market for electricity, high voltage | electricity, high voltage | Cutoff, U-NL" in the Ecoinvent 3.4.

Energy resource	Share	Remark
Solar power	0.01%	46.15% from, 3kWp slanted-roof installation, single-Si, photovoltaic panel; 53.85% from 3kWp slanted-roof installation, multi-Si, photovoltaic panel
Import	30.30%	Amongst the electricity import, 0.03% from the UK, 9.26% from Belgium; 74.08% from Germany, 16.63% from Norway
Nuclear	3.55%	Pressure waste reactor

Offshore windfarm	0.34%	1-3 MW offshore turbine
Onshore windfarm	4.02%	28.69% from <1 MW turbine, 53.18% from 1-3 MW turbine, 18.14%f from >3 MW turbine
Hydropower	0.10%	Run-of river
Other	1.55%	96.42% from heat and power co-generation by wood chips (6667 kW), 3.58% from heat and power co-generation by biogas
Coal	26.11%	74.59% from electricity production by hard coal, 25.41% from heat and power co-generation by hard coal
Gas	34.02%	17.62% from electricity production by natural gas with conventional, 24.62% from heat and power co-generation by natural gas with combined cycle power plant (400MW), 34.97% from electricity production by natural gas with the combined cycle power plant, 2.37% from heat and power co-generation by oil, 20.41% from heat and power co-generation by natural gas with the conventional power plant (100MW)

Table A6.11 Energy mix for electricity production in 2030 and 2050. Note: The source of energy mix share in 2030 is (EZK 2015); the energy mix share in 2050 is assumed based on the situation of 2030: the share of the renewable remain the same; the coal and gas are replaced by renewable sources. Those years between 2015 and 2030, and between 2030 and 2050 were through linear interpolation. The costs for heating and electricity were assumed to remain static.

Energy resource	Share in 2030	Share in 2050	Remark
Solar power	4.46%	8.88%	Same as 2015
Import	11.50%	22.90%	Same as 2015
Nuclear	2.35%	4.67%	Same as 2015
Offshore windfarm	14.32%	28.50%	Same as 2015
Onshore windfarm	11.27%	22.43%	Same as 2015
Hydropower	0.47%	0.93%	Same as 2015
Other	5.87%	11.68%	Same as 2015
Coal	16.43%	0.00%	/
Gas	13.62%	0.00%	/

Table A6.12 Construction/demolition/renovation waste intensity of the Netherlands. Note: The intensity of construction waste and demolition waste in the Netherlands was collected and modified based on the study (Zhang et al. 2020b, 2021c). The renovation waste from the cladding system for refurbishment is from the study (Villoria Sáez et al. 2018). It is assumed the lightweight concrete waste accounts for 1% of the gross normal-weight concrete waste. Besides, asbestos is assumed to only exist in the demolition waste of old buildings.

Waste intensity	Construction waste intensity for construction of new buildings [kg/m^2]	Demolition waste intensity for end-of-life buildings [kg/m^2]	Renovation waste intensity for renovation of old buildings [kg/m^2]
Concrete and other stony wastes	26.00	901.66	29.94
Ferrous and in non-ferrous metal	5.23	181.40	0.00
Wood	2.48	85.91	0.12
Glass	0.13	4.51	0.00
Plastic	0.31	10.70	0.07
Paper	0.09	3.10	0.19
Insulation	0.03	0.99	0.04
Asbestos	0.58	20.00	0.00
Sorting residue& mixed waste	5.77	200.13	0.25

Table A6.13 Recycling rate of each CDW (Mulders 2013). Note: the "Recycling rate within the Netherlands" means the geographic border of the Netherlands is the boundary for recycling rate statistics, and "export unknown recycling" is not included. In this assessment, the CDW for "export unknown recycling is assumed to be recycled in the Netherlands. The "*" represents recycling of this waste is considered for the calculation of gross CDW recycling rate in the Netherlands but the associated recycling impact is not considered. The shares of plastic and paper are negligible so the recycling impacts are not considered. Moreover, the recycling processes of insulation, gypsum, sorting residue& mixed waste are unknown, therefore, the recycling impacts of those waste are not considered.

Building materials	Recycling rate within the Netherlands	Recycling rate within the residential sector in the BAU and REB scenario	Recycling rate within the residential sector in the REN scenario
Concrete (and other stony wastes)	2%	2%	100%
Metal (ferrous and in non-ferrous)	78%	95%	95%
Wood	13%	23%	23%
Glass	100%	100%	100%
Plastics	17%	50%*	50%*

Paper	100%	100%*	100%*
Insulation	37%	37%*	37%*
Asbestos	0%	0%	0%
Gypsum	40%	40%*	40%*
Sorting residue& mixed waste	43%	43%*	43%*

Table A6.14 Space heating demand per annum of the ZABRA and TABULA nZEB standard. Note: The heating demand of the nZEB- EPISCOPE -NL is a net heating demand that excludes heat recovered by the ventilation system.

House type	Stock share	nZEB-ZEBRA-NL [kWh/(m²·annum)]	nZEB-EPISCOPE-NL [kWh/(m²·annum)]
Detached house	15.98%	/	12.30
Semi-detached	11.39%	/	9.20
Terraced house	33.60%	/	7.80
Apartment and maisonette	39.03%	/	7.40
In general		15.73	8.52

Table A6.15 The decarbonization goal of the residential built environment by 2030 and by 2050. Note: a) data from (CBS 2021b); b) data from (PBL et al. 2020) c) data from (EZK 2019); d) reduction by 95% based on 1990 level (21.5 Mt); e) data from the "A Roadmap for moving to a competitive low carbon economy in 2050" (EC 2011c), the emission of the residential and service sector is supposed to be reduced by 37%–53% by 2030 and reduced by 88%–91% by 2050.

	Historical emission of the residential built environment [a]	Decarbonization goal of the Netherlands	Decarbonization goal of the EU[e]
1990	21.5	/	/
1991	24.6	/	/
1992	22.7	/	/
1993	23.8	/	/
1994	22.3	/	/
1995	24.2	/	/
1996	28.1	/	/
1997	23.6	/	/
1998	22.5	/	/
1999	21.3	/	/
2000	21.3	/	/
2001	22.6	/	/
2002	21.8	/	/
2003	22.3	/	/

2004	21.3	/	/
2005	20.5	/	/
2006	20.7	/	/
2007	18.5	/	/
2008	20.9	/	/
2009	20.8	/	/
2010	24.1	/	/
2011	18.8	/	/
2012	20.1	/	/
2013	21.3	/	/
2014	16	/	/
2015	17.1	/	/
2016	17.7	/	/
2017	17.3	/	/
2018	17.2	/	/
2019	16.4	/	/
2030	/	14.1[b] -15.3[c]	10.1-13.5
2050	/	1.1[d] -1.5[c]	1.1-1.5