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Recycling potential in building energy renovation: A prospective study of the Dutch residential building stock up to 2050

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A B S T R A C T

Building energy and construction and demolition waste (CDW) are highly relevant but intertwined issues for the transition towards a carbon-neutral and circular built environment. Ongoing energy renovation uses an increasing number of emerging materials that pose a challenge for recycling. As a response, a novel technological system has been proposed to recycle CDW (including insulation mineral wool and lightweight concrete) for the manufacture of prefabricated concrete elements (PCEs) for use as façades for new (PCE-new) and retrofitting existing (PCE-refurbs) buildings. To explore how this novel system can improve recycling potential as part of building energy renovation efforts, the Dutch residential building stock was selected as a case study. Using a dynamic material flow analysis, we explore the supply-demand balance of secondary raw materials made from CDW (including normal-weight and lightweight concrete, glass, insulation mineral wool, and steel) and the secondary raw materials required for manufacturing PCEs in building energy renovation for the period 2015–2050. Our findings show that with advanced recycling technology, the secondary raw materials recovered from normal-weight concrete waste, glass waste, insulation mineral wool waste, and steel scrap will be more than sufficient to support the manufacturing of PCE-new walls, implying the possibility of closed-loop construction. However, for emerging materials such as lightweight concrete, the related waste will not be sufficient in the near future to meet the raw material demand for large-scale refurbishment with PCE-refurbs. Therefore, the Dutch case shows that the novel technology system offers a promising solution to CDW management problems in building energy renovation, but primary raw materials will still be needed for the increased use of emerging materials such as lightweight concrete.

1. Introduction

1.1. Potential of material circularity in building energy renovation

The building sector plays an essential role in resource depletion and waste management. The construction and operation of buildings in the European Union (EU) account for approximately half of all raw material consumption and generates approximately one-third of all waste (EC, 2014a). It is generally recognized that a circular economy—with the principle of "Reduce, Reuse, and Recycle (3R)"—should become the basis of circular waste management and material cycles (Kirchherr et al., 2017). Legislative systems for waste management in the EU were established based on the 3R rule (Sakai et al., 2011). Following this, circular construction adopts the 3R rule for construction and demolition waste (CDW) management (Ghaffar et al., 2020). The essence of circular construction is to keep the components and materials of buildings in a closed loop and maximize their value as long as possible (Benachio et al., 2020). Closing the construction loop by recycling CDW is considered an effective means of improving material efficiency and reducing the adverse impacts of CDW.

A significant challenge, however, is that almost 75% of the overall European building stock is energy-inefficient (EC, 2010).

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Abbreviations

3R	Reduce, reuse, and recycle
ADR	Advanced dry recovery technology
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
EED	Energy Efficiency Directive
EoL	End-of-life
EPBD	Energy Performance of Buildings Directive
EU	European Union
FRSCA	Fine recycled siliceous concrete aggregate
FRLWCA	Fine recycled lightweight concrete aggregate
HAS	Heating-air classification system
MFA	Material flow analysis
ODYM	Open Dynamic Material Systems Model
PCE	Prefabricated concrete element
PCE-new	Prefabricated concrete element for new building construction
PCE-refurb	Prefabricated concrete element for existing building refurbishment
RFUA	Recycled fiber wool ultrafine admixture
RGUA	Recycled glass ultrafine admixture
SI	Supporting information
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"

Considering the large amounts of greenhouse gasses emitted from the operation of buildings, improving energy efficiency is considered a critical strategy for achieving the EU's 2050 carbon-neutral goal (EZK, 2019). The EU deems building energy renovation as a critical solution to shift to an energy-efficient and low-carbon built environment (Esser et al., 2019). Energy renovation is an umbrella concept that is acknowledged as a variety of interventions in buildings to deliver different degrees of energy savings (Economidou, 2021). Moreover, employing advanced energy-efficient technologies in new construction also serves to establish a broader range of energy renovations (Esser et al., 2019). Accordingly, obsolete buildings in Europe are to be renovated or replaced to improve their energy performance, which increases the turnover of building materials as a result. Action 5 of Directive COM/2015/6317 (EC, 2015) calls for the "Development of new materials and technologies for the market uptake of energy efficiency solutions for buildings". In the context of extensive energy renovation in the EU, emerging high-performance materials such as insulating mineral wool, cellular and aerated glass, and lightweight concrete are increasingly used to reduce energy losses through building facades. Relative to 2015, the demand for such insulation materials is expected to increase in the EU by 3.5% by 2027 (Pavel and Blagoeva, 2018).

The demand for emerging materials to meet the demands of large-scale energy renovation not only increases the burden of resources but raises new problems surrounding their disposal. The main mineral-based insulating materials, such as stone wool and glass wool, are recyclable. One of the challenges for recycling is that insulation materials are lightweight, and the share of insulation also remains a small fraction of the total CDW. Therefore, the current EU weight-oriented CDW recovery targets and low disposal costs in some member states have no incentive to recycle insulating materials. In addition, the transport of insulation is costly because of its low weight-to-volume ratio. At the same time, concrete recycling is costly (Zhang et al., 2019), hence the recycling of common (normal-weight) concrete waste has not been popularized in the EU, not to mention the recycling of emerging lightweight concrete. Therefore, establishing a cost-effective recycling solution is expected to greatly help close the loop of these emerging materials and support a more circular built environment.

1.2. The Netherlands as a case study

The Netherlands has the best practice of CDW treatment among EU member states and worldwide, with a recovery rate of 98% (CLO, 2021). However, the Netherlands is also faced with the dilemma that the current destination for downcycled concrete—road base backfilling—is almost exhausted. Furthermore, extracting secondary raw materials from CDW via traditional wet-processing technologies for the building sector is costly (Zhang et al., 2019, 2020c·bib_Zhang_et_al_2019·bib_Zhang_et_al_2020c). For glass and insulation materials, it was reported that glass in CDW can be 100% recycled in the Netherlands; however, more than 60% of these insulation materials are landfilled and incinerated (Mulders, 2013). Moreover, in the Netherlands, more than half of the raw materials (gravel, sand, and cement) used for concrete production are dependent on imports (Zhang et al., 2020c). Another crucial point is that a large portion of the dwellings in the Netherlands remain energy-inefficient (Staniaszek, 2014). Therefore, the ongoing building energy renovation will likely further aggravate demand for resources in the Netherlands.

One potential possibility for simultaneously moving towards a circular and low-carbon built environment could be considering CDW as feedstock for building energy renovation. In Europe, a novel technological system has been developed by the 'VEEP' EU project for recycling CDW in the manufacturing of green prefabricated concrete elements (PCEs), offering high insulation performance for the renovation of the residential building stock. An advanced dry recovery system (ADR) and heating air classification system (HAS) were developed to recycle normal-weight and lightweight concrete waste *in situ*; and a dry grinding and refining (DGR) system was designed to recover glass waste and insulating mineral wool on-site. Consequently, recycled materials are used to fabricate green PCEs. The green PCE solution is conceived both for new building envelope construction (PCE-new) and for existing building envelope refurbishment (PCE-refurbs). Details of the PCE system are presented in the Supporting Information (SI).

To investigate whether the integrated PCE system offers a promising solution for CDW recycling in building energy renovation in the Netherlands, and whilst considering the increased use of emerging materials, we sought to determine the extent to which CDW can be recycled as a feedstock in building energy renovation using the Dutch residential building stock as a case study. We apply material flow analysis (MFA) as a widely-used method for evaluating material metabolism by mass in the anthroposphere (Baccini and Btunner, 2012). Among the three quantification approaches of MFA modeling defined by van der Voet (1996), dynamic MFA is usually applied to evaluate *ex-ante* and extrapolate trends. As we aim to unveil the recycling potential of emerging waste via an innovative recycling system, a dynamic MFA model was constructed for this study. Following the Introduction section, section 2 reviews the literature on MFA on CDW management; section 3 presents the dynamic MFA method and data sources; section 4 illustrates and discusses the results; and section 5 draws the conclusions.

2. Literature review

To explore the recyclability of CDW, many studies have been conducted using the MFA approach. To position our study, a systematic literature review of MFA application in the field of CDW management was conducted. Relevant literature was searched for in the Web of Science Core Collection from 1945 to 2020 (search terms: TS=("material flow analysis" OR "MFA") AND ("construction and demolition waste" OR "CDW")), yielding 32 results. After screening out five irrelevant studies, the remaining 27 studies are summarized in Table 1. It should be noted that this list is not exclusive.

Based on the literature review, MFA has been applied to investigate CDW at the product level (18, 21, and 26), building project level (17), regional level (1, 2, 3, etc.), and global level (13). The method has also been used in combination with life cycle assessment (10, 25, etc.) and life cycle costing (18) to evaluate the financial and environmental impact of CDW management. Most previous studies have focused on non-metallic mineral wastes such as concrete, whereas the recycling potential of emerging materials and renovation waste has not yet been examined.

Based on this review, regional-level dynamic MFA was selected for this study. Therefore, to fully consider the impact of the emerging waste (insulation mineral wool and lightweight concrete), we developed a dynamic MFA model to evaluate the supply-demand balance between the secondary raw materials made from CDW and the raw materials required for the manufacturing of PCEs for the period 2015–2050. Moreover, we explored how waste from energy renovation affects the mass accounting of CDW using dynamic MFA.

3. Methods and data sources

3.1. Conceptual framework

The estimation of the dynamics of the building stock was realized via a top-down modeling method based on gathered socio-economic data. A prospective approach was applied because MFA aims to explore the 'what-if scenario' of the future. As the waste flow was assumed to be determined by the change in stock, a stock-driven approach was used. Therefore, the MFA model applied to the Dutch case study presents a prospective, top-down, stock-driven model.

Müller (2006) developed a stock-driven model for estimating the diffusion of concrete in residential stock in the Netherlands from 1900 to 2100. Based on Müller's modeling approach, we applied a three-layer stock dynamics model, as illustrated in Fig. 1. The dwelling layer is the key layer for steering the turnover of the building stock. As part of the dwelling layer, data on population, floor area per capita, and building lifetime probability distribution were collected to calculate the construction, renovation, and demolition floor area for each year of study. Within the PCE layer, a geometry coefficient was used to determine the demand of PCE-new and PCE-refurbs per floor area of building construction and renovation. The outflow of the end-of-life (EoL) PCE was not considered because it is assumed to occur much later than the temporal scope of the accounting system. Finally, under the material layer, the waste intensity, material intensity, and recycling rate were investigated to understand the supply and demand conditions of secondary raw materials.

3.2. Goal and scope definition

The goal of the MFA model was to estimate material inflows and outflows of the residential building stock of the Netherlands to support decision-making on the potential of material circularity in prefabrication-based building energy renovation. The geographical boundary of the assessment was the border of the Netherlands. The temporal scope of the assessment was from 2015 to 2050. Non-residential buildings, such as hospitals and schools, were excluded. The anthropogenic cycle of building materials is generally considered to consist of five life phases, as shown in Fig. 2; we focused on the recycling phase only, in which CDW was assumed to be reprocessed to manufacture secondary raw materials. For waste and materials to be tracked, we focused on the target CDW and secondary raw materials, as shown in the dotted box in Fig. 2.

3.3. Characterization of parameters

3.3.1. Population

Historical population from 1900 to 2015 (CBS, 2019a) and forecasted population from 2015 to 2050 (CBS, 2019b) data were obtained for the Netherlands as shown in Fig. 3(a).

3.3.2. Residential floor area per capita

To the authors' knowledge, there are no statistics available on the historical and forecasted residential floor area per capita in the Netherlands. Müller simulated the floor area per capita in the Netherlands from 1900 to 2100 based on the United Nations' average value (Müller, 2006). Here, we used the standard flood area per capita scenario from 1900 to 2050, as shown in Fig. 3(b).

3.3.3. Construction, demolition, and renovation

Computation of the construction and demolition floor area was based on the concept of building stock dynamics in Fig. 1 and an operable Python-based framework called the 'Open Dynamic Material Systems Model' (ODYM) developed by Pauliuk and Heeren (2020). We extended the ODYM using an additional renovation function, where the residential building stock was calculated using Eq. (1):

$$S(t) = P(t)F(t) \tag{1}$$

where $S(t)$ is the gross residential floor area of year t (1900, 2050); $P(t)$ is the population of year t (1900, 2050); and $F(t)$ is the residential floor area per capita in year t (1900, 2050).

The newly constructed floor area for year t is given by Eq. (2):

$$A_{new}(t) = S(t) - S(t-1) + A_{dem}(t) \tag{2}$$

where $A_{new}(t)$ is the new construction floor area of year t (1900, 2050) and $A_{dem}(t)$ is the demolition floor area in year t (1900, 2050).

The annual demolition rate was modeled through Eqs. (3)–(6). $L(t, t')$ in Eq. (4) is a probability distribution function that presents the probability that buildings built in year $t' < t$ will be demolished in year t. The lifetime distributions of buildings are commonly estimated with normal, log-normal, and Weibull distributions, although no evidence is available to indicate which probability distribution is best suited for dynamic stock modeling (Miatto et al., 2017b; Müller, 2006). Therefore, we used a modified Weibull statistical distribution to approximate the lifetime of residential buildings in the Netherlands. The Weibull random variables t and t' are characterized by the shape parameter k and a scale parameter λ. The shape parameter $k = 2.95$ is specified according to the average

Table 1
Literature related to material flow analysis of construction and demolition waste (CDW).

	Literature	Model	Region	Study aims/notes
1	Lederer et al. (2020)	Static, 2014	Vienna	MFA was used to quantify how waste reduction, re-use, and recycling of mineral CDW from buildings and infrastructure can contribute to reducing the demand for raw material imports for construction minerals.
2	Zhang et al. (2020c)	Static, 2015, 2025	The Netherlands	Quantifies how technological innovation could contribute to upgrading waste concrete treatment from downcycling to recycling.
3	Marcellus-Zamora et al. (2020)	Static, 2007–2017	Philadelphia, USA	Characterizes the flow of recoverable CDW, quantify aggregated CDW diversion, and evaluate recycling patterns for a portion of the CDW.
4	Gassner et al. (2020)	Dynamic, 1990–2015	Vienna	Estimation of material turnover of urban transport systems, including both infrastructure and vehicles.
5	Wu et al. (2020)	Static, 2007–2017	Australia	Quantifies the compositions and generation of CDW and to reveal its cross-regional mobility.
6	Noll et al. (2019)	Dynamic, 1971–2016	Samothraki, Greece	Strategy design on reducing, reusing, and recycling CDW on islands where waste treatment options are limited.
7	Tangtinthai et al. (2019)	Static, 2012	Great Britain, Thailand	Examines relevant policies on how to achieve more sustainable management of concrete and cement.
8	Heeren and Hellweg (2019)	Dynamic, 2015–2055	Switzerland	Used a bottom-up probabilistic modeling approach to determine material stocks in Swiss residential buildings and associated carbon emissions.
9	Jain et al. (2019)	Dynamic, 2012–2050	India	A bottom-up approach to explore how CDW generation rate varies across different classes of cities.
10	Zhang et al. (2018)	Static, 2015	Chongqing, China	Explores the carbon mitigation and land-use reduction of different strategies for concrete waste management.
11	Suzuki et al. (2018)	Dynamic, 1981–2015	Japan	Investigates the potential fate of engineered nanomaterials in the construction sector.
12	Miatto et al. (2017c)	Dynamic, 1905–2015	USA	A bottom-up stock-driven model to evaluate long-term metabolism, and materials accumulated in the road network.
13	Miatto et al. (2017a)	Dynamic, 1970–2010	Worldwide	Estimates the extraction of nonmetallic minerals and associated uncertainty about consumption by different sectors.
14	Schiller et al. (2017)	Dynamic, 1919–2010	Germany	Analyzes and quantifies the entire material cycle of bulk nonmetallic mineral building materials by considering the use of recycled aggregates in concrete building elements.
15	Condeixa et al. (2017)	Dynamic, 2000–2010	Rio de Janeiro, Brazil	A bottom-up approach to assess the materials in-use and further flows of CDW from the residential building stock.
16	Lockrey et al. (2016)	Static, 2002–2025	Hanoi, Vietnam	Estimates construction and demolition concrete waste in Hanoi and Vietnam.
17	Li et al. (2016)	Static, did not specify a time	A six-story building in Hebei, China	Proposes a model at a project level to quantify construction waste for building construction projects.
18	Dahlbo et al. (2015)	Static, did not specify a time	Product-level, Finland	A combined method to holistically evaluate the environmental and economic performance of the CDW management system.
19	Wiedenhofer et al. (2015)	Dynamic, 2004–2009	EU25	Quantifies stocks and flows for nonmetallic minerals in residential buildings, roads, and railways.
20	Hu et al. (2013)	In general	In general	Examines concrete recycling as a case study to illustrate a framework of life-cycle sustainability analysis combining MFA with life-cycle analysis.
21	Knoeri et al. (2013)	Static, did not specify a time	Product level	Provides a product- comparison of conventional concrete and concrete with recycled aggregates.
22	Hoque et al. (2012)	Static, 2001	Catalonia, Spain	Analyzes resource consumption in the construction sector.
23	Chong and Hermreck (2011)	Static, 2005, 2006	Las Vegas, Kansas, Portland, Seattle, USA	Quantifies energy demand for transporting and recycling construction steel.
24	Hu et al. (2010)	Dynamic, 1949–2050	Beijing, China	Quantifies the CDW in Beijing to support strategic waste management.
25	Kapur et al. (2009)	Static, 2000–2004	USA	Develops a country-level stock and flow model to investigate the life-cycle of cement.
26	Weil et al. (2006)	Static, did not specify a time	Product-level, Germany	A micro-level comparison of the environmental benefits of (per m^3) of concrete with or without recycled aggregates.
27	Bertram et al. (2002)	Static, 1994	16 European countries	Copper mass balance assessment for waste management in multiple European countries.

level of buildings in Western Europe (Deetman et al., 2020). The scale parameter $\lambda = 134.48$ was determined as the average lifetime of Dutch residential buildings (E_{LF}), as shown in Eq. (5), in which $\Gamma(x)$ represents the gamma function as presented in Eq. (6). Müller (2006) compared different lifetimes for the Dutch building stock, specifically short (60 years), medium (90 years), and long (120

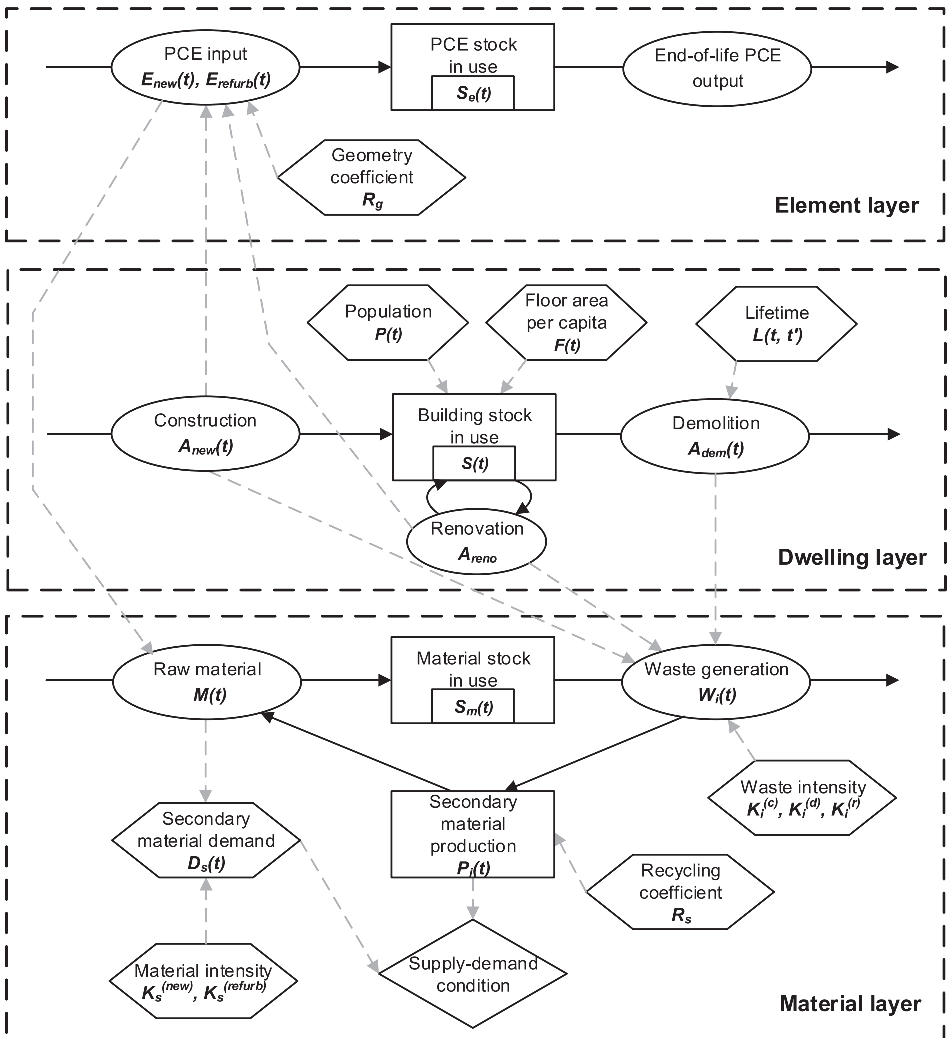

Fig. 1. Conceptual framework of a three-layer dynamic material flow analysis model. Note: hexagons indicate drivers and determinants, rectangles represent processes, ovals with solid lines denote flows, and dashed lines with arrows denote influences between two variables.

years). Deetman et al. (2020) found that estimations only match statistical data when a high average lifetime (130 years) of buildings in Western Europe is assumed. Thus, the average lifetime was assumed to be 120 years in our building stock modeling, as adopted by Sandberg et al. (2016). The resulting lifetime distribution of residential buildings in the Netherlands is shown in Fig. 3(c).

$$A_{dem}(t) = \int_{t_0}^{t} A_{new}(t')L(t,t')dt' \tag{3}$$

$$L(t,t') = \begin{cases} k\lambda^{-k}(t-t')^{k-1}e^{-\frac{(t-t')^k}{\lambda^k}}, & t' < t \\ 0, & t' \geq t \end{cases} \tag{4}$$

$$\lambda = E_{LF} \Big/ \Gamma\left(1 + \frac{1}{k}\right) \tag{5}$$

$$\Gamma(x) = \int_{0}^{\infty} t^{x-1}e^{-t}dt \tag{6}$$

The assumptions for the renovation of obsolete buildings were as follows: 1) Renovation started from t = 2015 to 2050; 2) buildings to be retrofitted were constructed from t' = 1900 to 2014; buildings constructed after 2014 were not retrofitted; 3) buildings to be renovated were separated from those buildings to be demolished, i.e., buildings that are supposed to be demolished by 2050 will not be renovated; 4) renovation floor area per annum was calculated based on Eq. (7). The gross floor area for renovation was equally allocated to each year between 2015 and 2050, amounting to an approximately 17 million m^2 floor area to be renovated per annum; and 5) for those buildings to be renovated, older buildings were preferentially renovated. The simulation results of the construction inflow, demolition outflow, and floor area for the renovation of each year are shown in Fig. 3(d), and the dynamics of the building stock specified by construction cohorts are presented in Fig. 3(e). The renovation of buildings in different construction periods (cohorts) is shown in Fig. 3(f).

$$A_{reno} = \frac{S(2050) - \sum_{t'=2015}^{2050}\left\{A_{new}(t') - \sum_{t=t'}^{t=2050}\left[\int_{t'}^{t} A_{new}(t')\cdot L(t,t')dt'\right]\right\}}{2050 - 2014} \tag{7}$$

where A_{reno} is the renovation floor area in year t (2015, 2050).

3.3.4. Demand of PCEs per floor area

The Agentschap NL of the Ministry of the Interior and Kingdom Relations in the Netherlands publishes data on the type and construction vintage of residential buildings. Agentschap NL (2011) categorizes Dutch residential buildings into detached houses, semi-detached houses, terraced houses, maisonette houses, and apartments, and provides data on the number of houses and average floor area of each house type until 2005. The modified stock share of each building typology based on the Agentschap NL report is shown in Table 2. Details of the modifications are provided in the SI. We assumed that the share (m^2) of each housing category remains constant until 2050.

The required amount of PCEs (m^2) can be calculated based on the external wall surface and floor area of a building. To estimate the requirement of PCEs, we introduced a geometry coefficient (R_g) to denote the ratio of the gross external wall surface compared to the gross floor area of a building. The TABULA database contains comprehensive information about the typology of residential buildings for 21 European states. Yang et al. (2020) used this database to measure the geometric information of buildings in Leiden, the Netherlands. Here, R_g data for the different types of buildings were collected from the TABULA database (2017), as shown in Table 2.

The weighted geometry coefficient of the Dutch building stock is $R_g = 0.57$, which was calculated using Eq. (8):

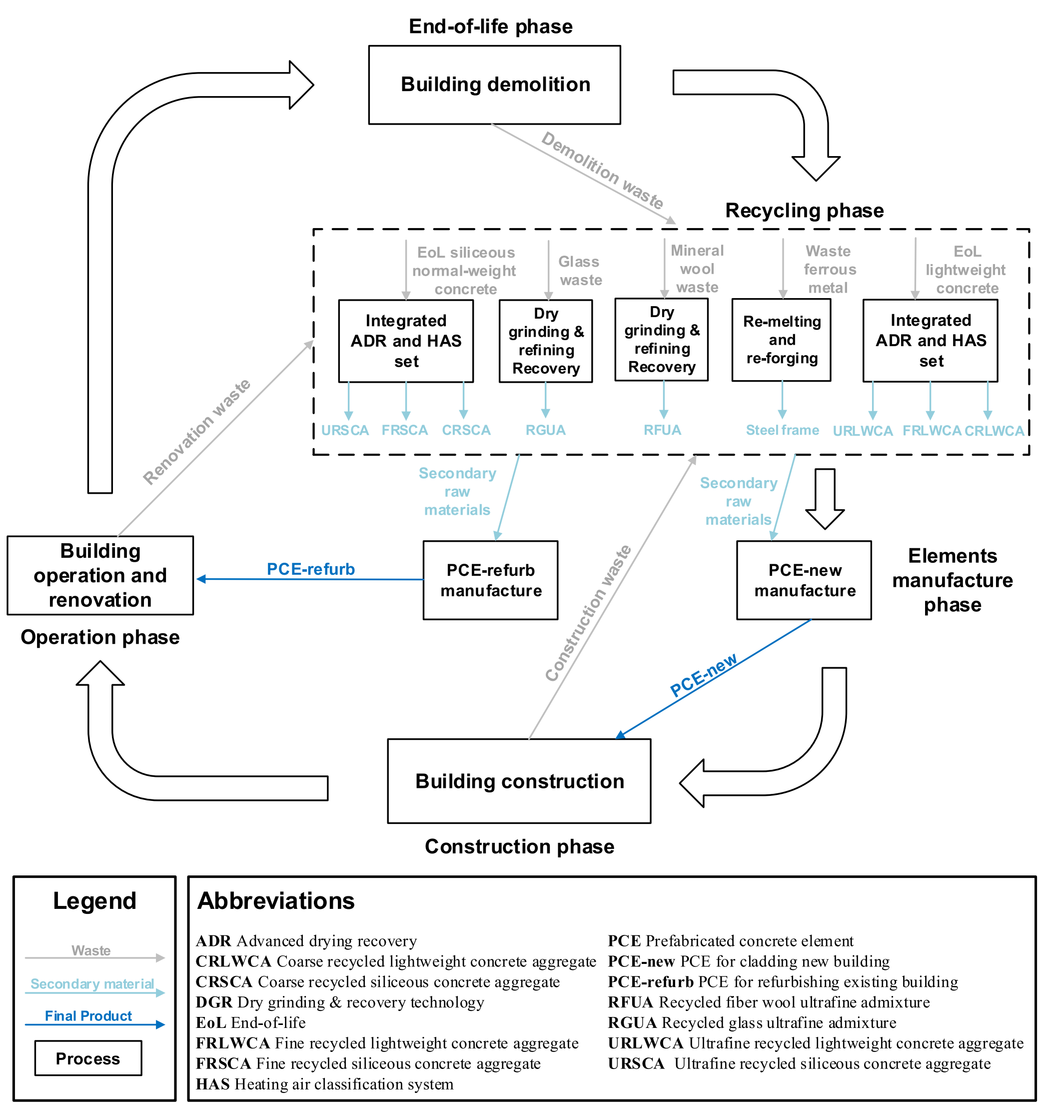

Fig. 2. System boundary of the material flow analysis. Note: wastes and materials to be tracked in the system are shown in the dotted box.

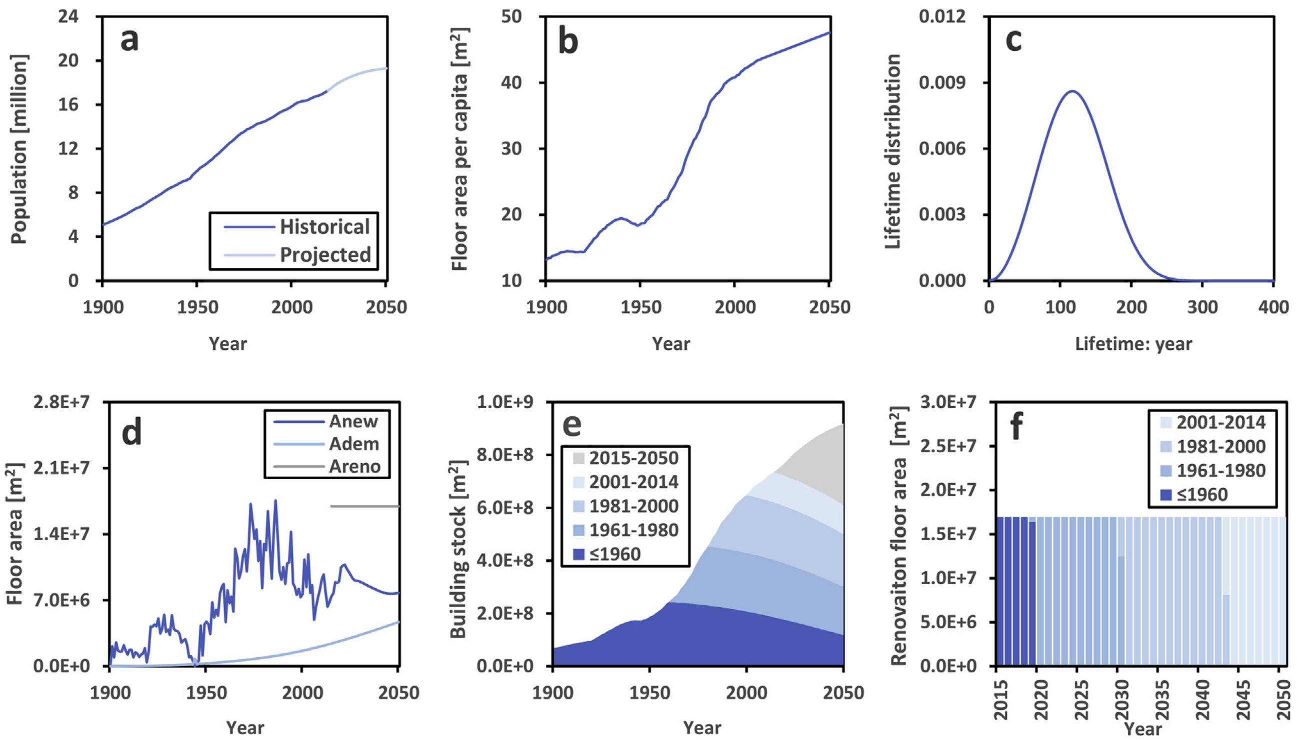

Fig. 3. Estimation of parameter functions and simulation results for the Netherlands: (a) presents the historical and forecast population from 1900 to 2050; (b) demonstrates residential floor area per capita from 1900 to 2050; (c) shows the Weibull statistical distribution for modeling lifetime of dwellings; (d) presents construction, demolition, and renovation floor area of each year; (e) shows the dynamics of the building stock specified by construction cohorts; and (f) illustrates the vintage cohort of buildings to be renovated each year.

Table 2
Ratio of external wall surface and floor area for different types of residential buildings in the Netherlands.

Building type	Stock share ($R_{stock}^{(bt)}$)	Building demonstrator	Reference code in the TABULA database	Construction vintage	External wall surface [m^2] ($S_{wall}^{(bt)}$)	Floor area [m^2] ($S_{floor}^{(bt)}$)	Geometry coefficient ($R_g^{(b)}$)
Detached house	15.98%		NL.N.SFH.03.Deta	1975–1991	144.00	169.00	0.85
Semi-detached house	11.39%		NL.N.SFH.01.Semi	Before 1964	97.80	121.00	0.81
Terraced house	33.60%		NL.N.TH.01.Mid1964	Before 1964	42.30	96.00	0.44
Maisonette	24.38%		NL.N.AB.02.Mai	1965–1974	598.40	1355.00	0.44
Apartment	14.65%		NL.N.AB.02.Por	1965–1974	951.40	1562.00	0.61

$$R_g = \sum \left[\left(\frac{S_{wall}^{(bt)}}{S_{floor}^{(bt)}} \right) R_{stock}^{(bt)} \right] \quad (8)$$

where R_g is the weighted geometry coefficient of the Dutch building stock, $S_{wall}^{(bt)}$ is the gross external wall surface of a certain type of reference building, $S_{floor}^{(bt)}$ is the gross floor area of a certain type of reference building, and $R_{stock}^{(bt)}$ is the gross stock of a certain building type.

3.3.5. Generation of CDW

CDW yielded from construction, demolition, and renovation activities were estimated using Eq. (9):

$$W_i(t) = A_{new}(t) K_i^{(c)} + A_{dem}(t) K_i^{(d)} + A_{reno}(t) K_i^{(r)} \quad (9)$$

where $W_i(t)$ is the waste i generated in year t; $A_{new}(t)$ is the new construction floor area of year t; $A_{dem}(t)$ is the demolition floor area

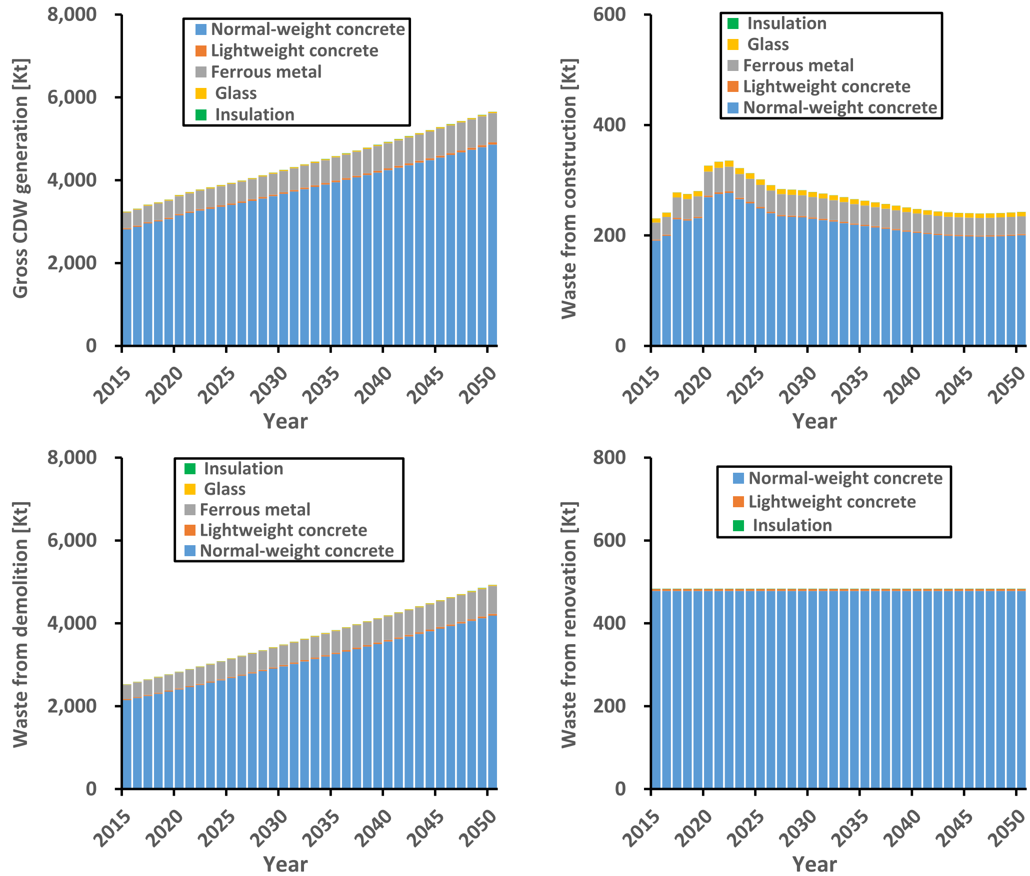

Fig. 4. Estimated construction and demolition waste (CDW) generated from the construction, demolition, and renovation in the Netherlands for the period 2015−2050.

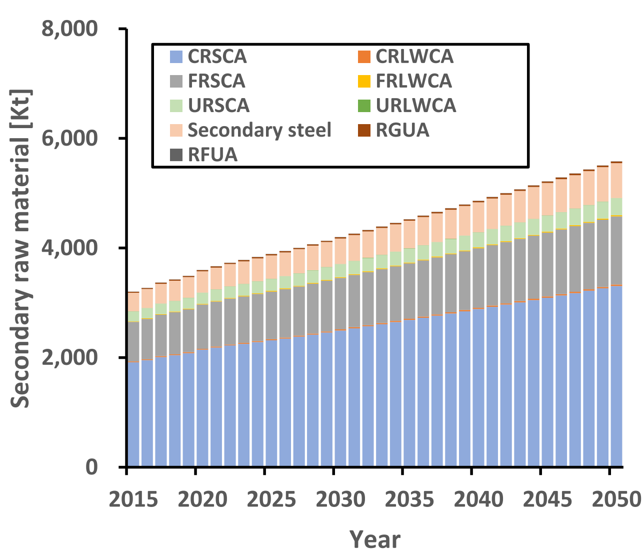

Fig. 5. Potential productive capability of secondary raw materials in the Netherlands for the period 2015−2050.

in year t; $A_{reno}(t)$ is the renovation floor area of year t; $K_i^{(c)}/K_i^{(d)}/K_i^{(r)}$ is construction/demolition/renovation waste intensity coefficient: the amount of waste i generated per construction/demolition/renovation floor area. The data sources for each parameter are presented in the SI.

As an emerging material, lightweight concrete is not yet widely used in Europe (Thienel et al., 2020). The average lifespan of buildings in the Netherlands was assumed to be 120 years, and buildings to be demolished were mainly constructed around the 1900s. Thus, most concrete waste in the CDW is normal-weight concrete waste. Therefore, we conservatively assumed that the gross concrete waste contained 1% lightweight concrete (by weight). According to the insulation material market in Europe, insulating mineral wool accounts for 58% of the insulation material by weight (Pavel and Blagoeva, 2018). Based on these assumptions, the estimated amounts of concrete waste, glass waste, ferrous waste, and insulation waste generated between 2015 and 2050 are presented in Fig. 4.

3.3.6. Production of secondary raw materials

The production of secondary raw materials was calculated according to Eq. (10):

$$P_s(t) = W_i(t)R_s \tag{10}$$

where $P_s(t)$ represents the amount of secondary raw material made from waste i in year t, and R_s denotes the recycling coefficient of production of secondary raw material from waste. The data sources for each parameter are presented in the SI. The potential productive capability of secondary raw materials via recycling waste is presented in Fig. 5.

3.3.7. Demand for secondary raw materials

The secondary raw material demand of PCE-new and PCE-refurbs were computed using Eq. (11):

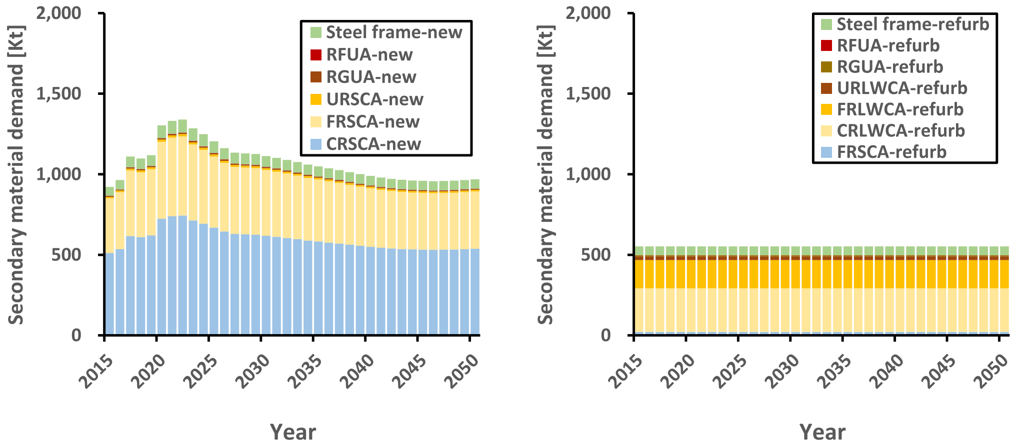

Fig. 6. Secondary raw material demand for the manufacture of PCE-new (left) and PCE-refurb (right) in the Netherlands for the period 2015–2050.

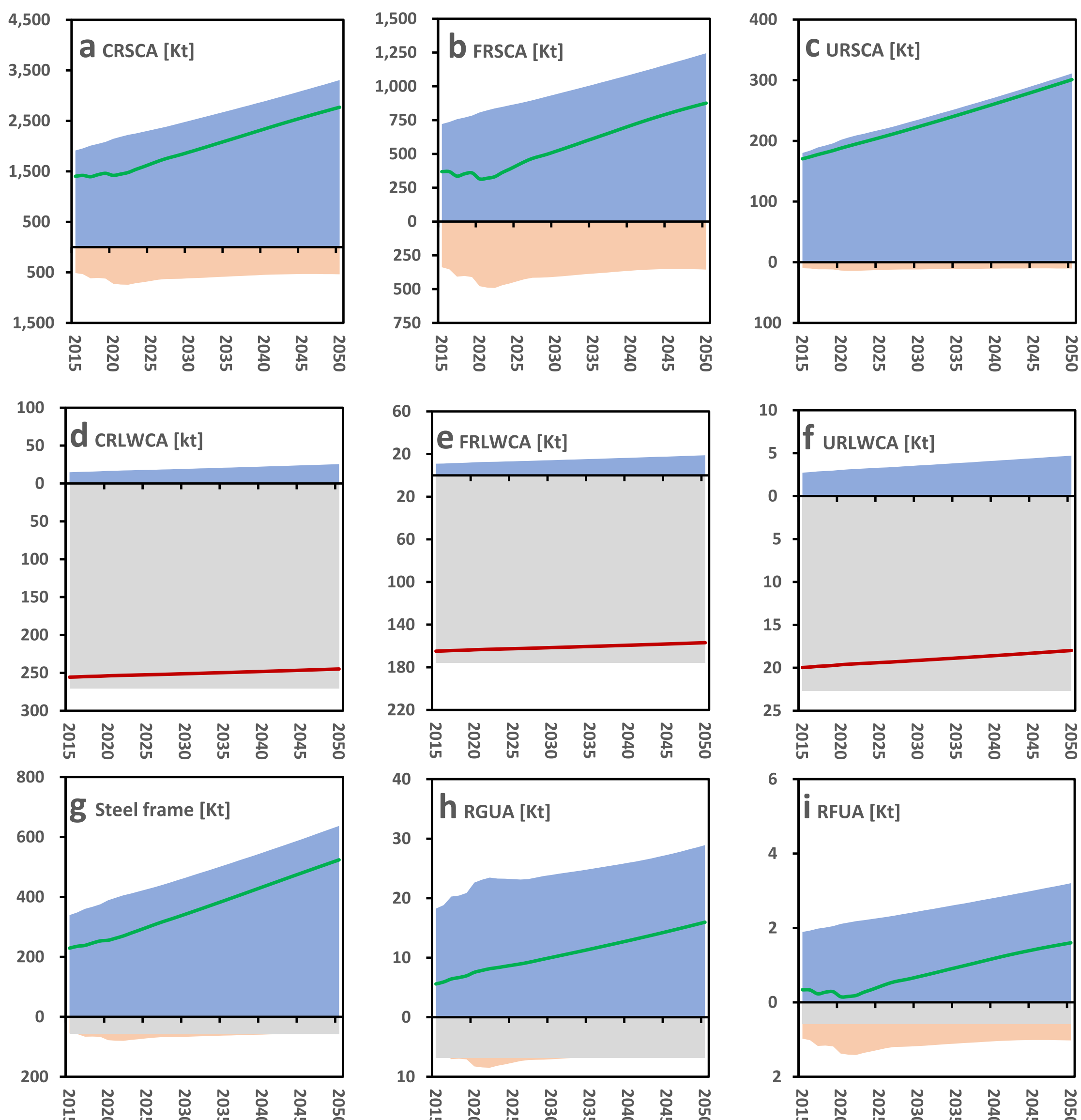

Fig. 7. Supply-demand condition of secondary raw materials. Note: 1) zone (in blue) above 0 represents the supply of secondary raw materials, zone below 0 represents the demand of secondary raw materials for building construction (in salmon) and building renovation (in grey); 2) curves in red indicate the deficient amount of secondary raw materials, curves in green indicate the surplus amount of secondary raw materials.

$$D_s(t) = A_{new}(t)K_s^{(new)} + A_{reno}K_s^{(refurb)}, \tag{11}$$

where $D_s(t)$ is the secondary raw material demand in year t, $A_{new}(t)$ is the construction floor area of year t, A_{reno} is the renovation floor area of each year, $K_s^{(new)}$ is the secondary raw material demand of PCE-new per construction floor area; and $K_s^{(refurb)}$ is the secondary raw material demand of PCE-refurbs per renovation floor area. The data sources for each parameter are presented in the SI. Based on these calculations, the total secondary raw materials required for the implementation of the PCE-new and PCE-refurbs are presented in Fig. 6.

4. Results and discussion

4.1. Supply-demand analysis

Based on the potential supply of secondary raw materials (see Fig. 5) and the demand for secondary raw materials for construction and renovation (see Fig. 6), the supply and demand balance of each secondary raw material is presented in Fig. 7. Based on this, the secondary raw materials (CRSCA, FRSCA, and URSCA) for PCE-new can be supplied in sufficient quantities, even with surplus quantities. The demand for steel frames, RGUA, and RFUA can also be fully met.

The CRLWCA, FRLWCA, and URLWCA for the production of PCE-refurbs are inadequate, however, to support significant refurbishment efforts. The deficit portion of these materials could be complemented by using virgin materials (e.g., expanded clay, sand, and cement) or by importing lightweight concrete waste from neighboring countries such as Germany or Belgium, although this is unlikely due to high transportation costs.

4.2. Comparison of secondary material surplus and primary material imports

The surplus or deficit of each secondary raw material was compared to the net import of the corresponding virgin raw material. The associated import and export data were collected from the UN Comtrade database (2020). Because the data on iron and steel are presented as monetary values in the database, the comparison of these materials with reforged steel was excluded. For the comparison of gravel and CRSCA in Fig. 8(a), the median trend of gravel net imports is approximately five times that of CRSCA since 2018; however, under conservative (lower confidence limit) conditions, the surplus of CRSCA can substitute all gravel imports from 2040 onwards. Concerning the net import of expanded clay in Fig. 8(b), the overall volume is considerably smaller than that of

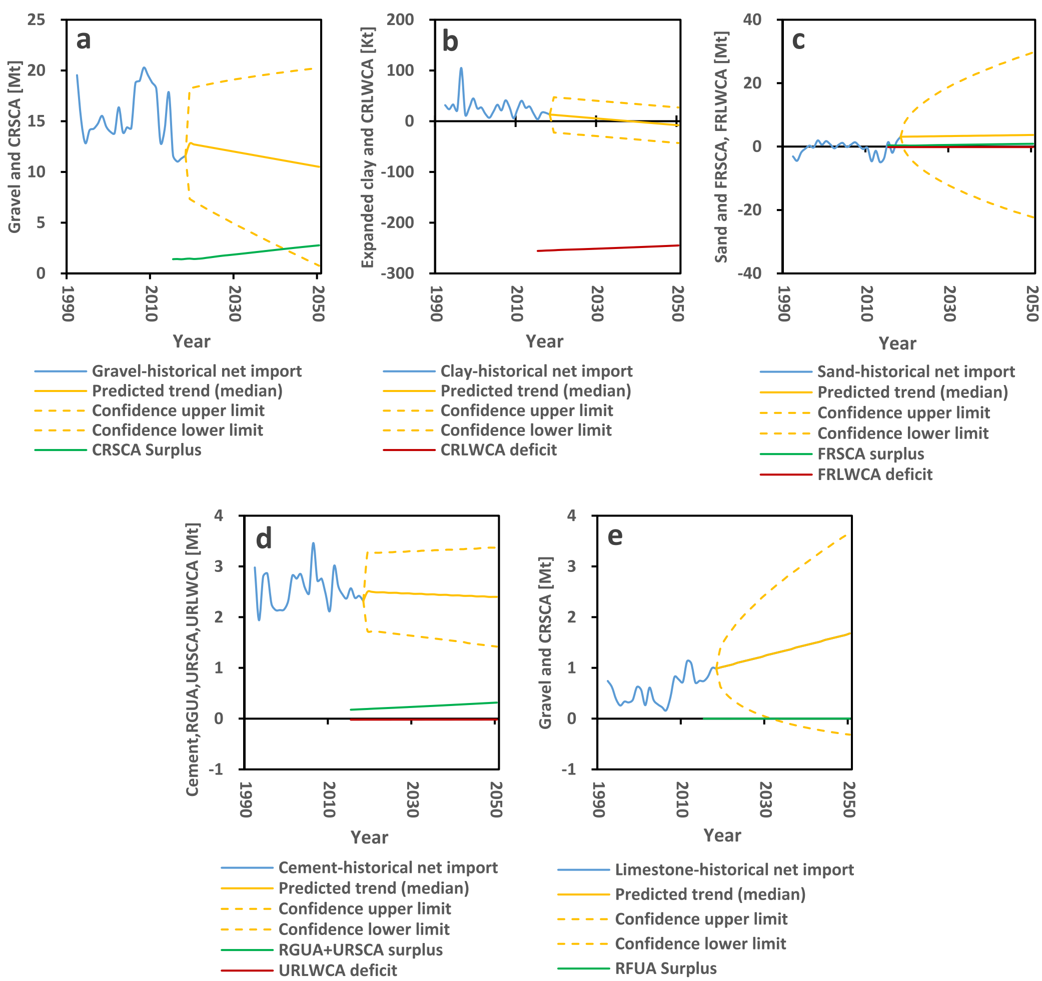

Fig. 8. Comparison between virgin raw material net import (import subtracts export) and secondary raw material deficit and surplus in the Netherlands for the period 1990–2050: (a) represents the comparison of gravel net import and CRSCA surplus; (b) denotes comparison of expanded clays net import and CRLWCA deficit; (c) compares sand net import, and FRSCA surplus, and FRLWCA deficit; (d) compares cement net import, RFUA + URSCA surplus, and URLWCA deficit; and (e) compares limestone net import and RFUA surplus. Data were collected from UN Comtrade database (2020). The predicted trends were obtained via linear regression with a 95% confidence interval.

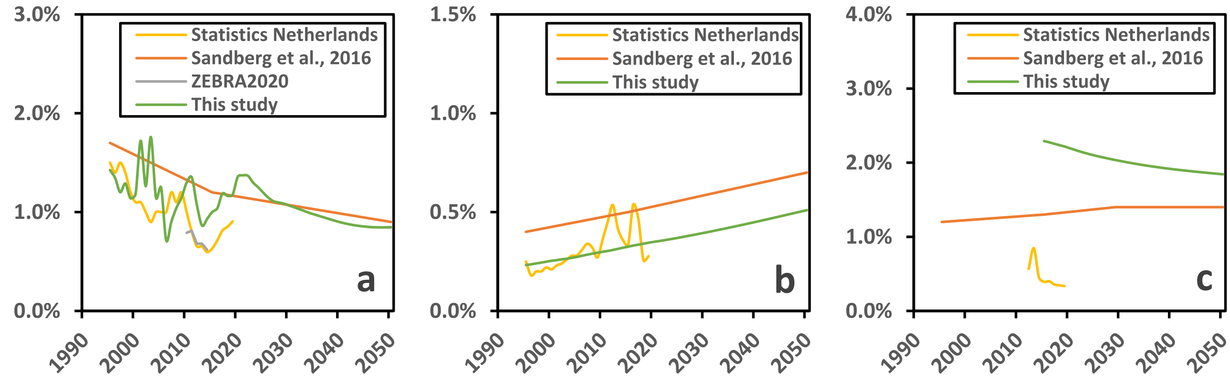

Fig. 9. Comparison of (a) construction rate, (b) demolition rate, and (c) renovation rate for the Netherlands based on a range of sources.

gravel, fluctuating from 5 to 100 Kt between 1992 and 2018, and probably continuing to decrease to 2050. The deficit of CRLWCA stabilizes at approximately 180 Kt, which may cause the import of expanded clay to increase in the future.

For virgin sand imports in Fig. 8(c), compared to the other raw materials, sand relies less on imports according to the trend of historical net imports, although with a large uncertainty range. The surplus of FRSCA and the deficit of FRLWCA are insignificant compared to the large uncertainty in net imports. In the case of the cement import in Fig. 8(d), as with the net import trend of gravel, the Netherlands is and will be largely dependent on imports. The amounts of RGUA and URSCA surpluses and the URLWCA deficit are negligible compared to imports. Lastly, as shown in Fig. 8(e), the net import of limestone follows an increasing trend. As insulation waste only accounts for less than 0.1% of the total CDW, the RFUA produced from insulation waste has an almost negligible effect on the import of limestone.

4.3. Calibration and uncertainty

The dynamic MFA model is based on multiple parameters, and the fluctuations of each parameter will, therefore, affect the final supply and demand balance. Owing to the lack of a valid reference for the fluctuation range of each parameter, it is impossible to conduct a full uncertainty analysis. Nevertheless, an examination of the uncertainty was performed based on those factors with a relatively strong influence on the results. Thus, we deem that the biggest uncertainties lie in the estimation of 1) annual construction, demolition, and renovation floor area; 2) concrete waste intensity; and 3) the share of lightweight concrete waste in gross concrete waste.

4.3.1. Annual construction, demolition, and renovation

The annual construction, demolition, and renovation floor area in this study were validated in reference to other data sources, the Environmental Assessment Agency (Staniaszek, 2015), the ZEBRA2020 Data Tool (2020), Sandberg et al. (2016), and Statistics Netherlands (2020). Some of these sources measured the turnover of the building stock based on the number of dwellings instead of floor area, which makes their results incomparable. Therefore, we used relative indexes, namely construction rate, demolition rate, and renovation rate, to unify the comparison. Based on Fig. 9(a), all of the construction rates present a decreasing trend from approximately 1.5%–1%, while in Fig. 9(b), demolition rates show a gradually increasing trend from approximately 0.3%–0.5%. These renovation rates from the different sources demonstrate a notable disparity. Overall, the construction and demolition rates we

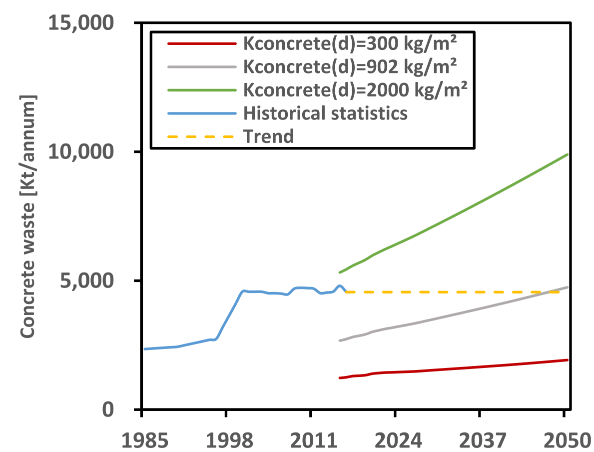

Fig. 10. Concrete waste generation from the residential building sector in the Netherlands under different waste intensities. Note: $K_{concrete}$ denotes the waste concrete waste intensity for demolition.

applied in this study are in general accordance with these other sources.

As shown in Fig. 9(c), the average historical renovation rate from Statistics Netherlands is approximately 0.5% while the renovation rates of other sources are much higher. To achieve the carbon-neutral goal by 2050, of the 7.5 million dwellings, 170,000 need to be renovated per annum in the Netherlands (Staniaszek, 2015). Based on this, the equivalent renovation rate was set at 2.3% in 2015, amounting to approximately 17 million m^2 per annum.

4.3.2. Concrete waste intensity

Concrete waste was the focal waste stream of our CDW estimates. The concrete waste intensity for demolition ($K^{(d)}_{concrete} = 902$ kg/m^2) has a far greater contribution to gross concrete waste generation than construction ($K^{(c)}_{concrete} = 26$ kg/m^2) and renovation ($K^{(r)}_{concrete} = 28.5$ kg/m^2. Therefore, the uncertainty in waste concrete generation from building demolition ($K^{(c)}_{concrete}$) is discussed further in this section.

Concrete waste is commonly generated from four sectors: (1) the residential building sector, (2) the non-residential building sector, (3) civil engineering, and (4) the building materials industry. Concrete waste produced from the residential sector accounts for approximately 30% of the gross concrete waste in the Netherlands (Zhang et al., 2020c), and the Environmental Data Compendium of the Netherlands (CLO) (2020) reported the generation of CDW between 1985 and 2016. Based on this, we estimated the concrete waste generated from residential buildings, as shown in Fig. 10. These data show that the concrete waste released from residential buildings has stabilized at approximately 4500 Kt per annum since 2000.

Notably, the concrete waste intensity varies for different types of buildings. For example, a timber-structured building generates up to 300 kg/m^2 of concrete waste (Gálvez-Martos et al., 2018). For concrete structure buildings, relevant data from a demolition project located on the de Kempkensberg in Groningen in the Netherlands (Hu et al., 2012) were collected to estimate the concrete waste intensity. This concrete high-rise building had 14 stories and a 6174 m^2 of useful floor area, from which a total of 12,357 tons of concrete waste was generated during demolition, amounting to 2 tons of concrete per m^2 of floor area. This is in accordance with the medium-level concrete waste intensity of 2.1 t/m^2 in Müller's stock dynamics modeling (Müller, 2006). The amounts of concrete waste based on different concrete intensities (300 kg/m^2, 902 kg/m^2, and 2000 kg/m^2) were compared, as shown in Fig. 10. If $K^{(d)}_{concrete}$ increases to 2000 kg/m^2, gross concrete waste shows a sharply increasing trend. In contrast, at 300 kg/m^2, this trend is less than half of the historically probable trend. The selected median value (902 kg/m^2) was also lower than the actual trend. Therefore, the estimation of concrete waste in this study was relatively low compared to the reality. This may be because we assumed a high lifetime for residential buildings, leading to less generation of demolition waste. Moreover, we used static concrete waste intensity, whereas waste intensity is likely to increase over time.

4.3.3. Share of lightweight concrete waste

According to the Reports and Data (2020), the global lightweight aggregate concrete market was valued at 37.2 billion USD in 2018 and is expected to reach 56.7 billion USD by 2026. In Europe, the lightweight aggregate concrete market is forecasted to increase from 23 million USD in 2018 to 40 million USD in 2026 (Reports and Data, 2020). The share of lightweight concrete waste compared to gross concrete waste is assumed to remain stable at 1% until 2050. Quantification of the variations in this share can provide a more comprehensive assessment of the supply-demand connection. Therefore, we examined the level of uncertainty by modeling several scenarios in which the share of lightweight concrete waste would increase at different rates over time. The share was modeled starting with different initial values (1%, 3%, and 5%) and then increased linearly to 8%, 12%, and 20% between 2015 and 2050.

The results of the uncertainty simulation are shown in Fig. 11. Under all conditions, the URLWCA is likely to be sufficiently supplied. For CRLWCA and FRLWCA, when the initial share is 1%, even

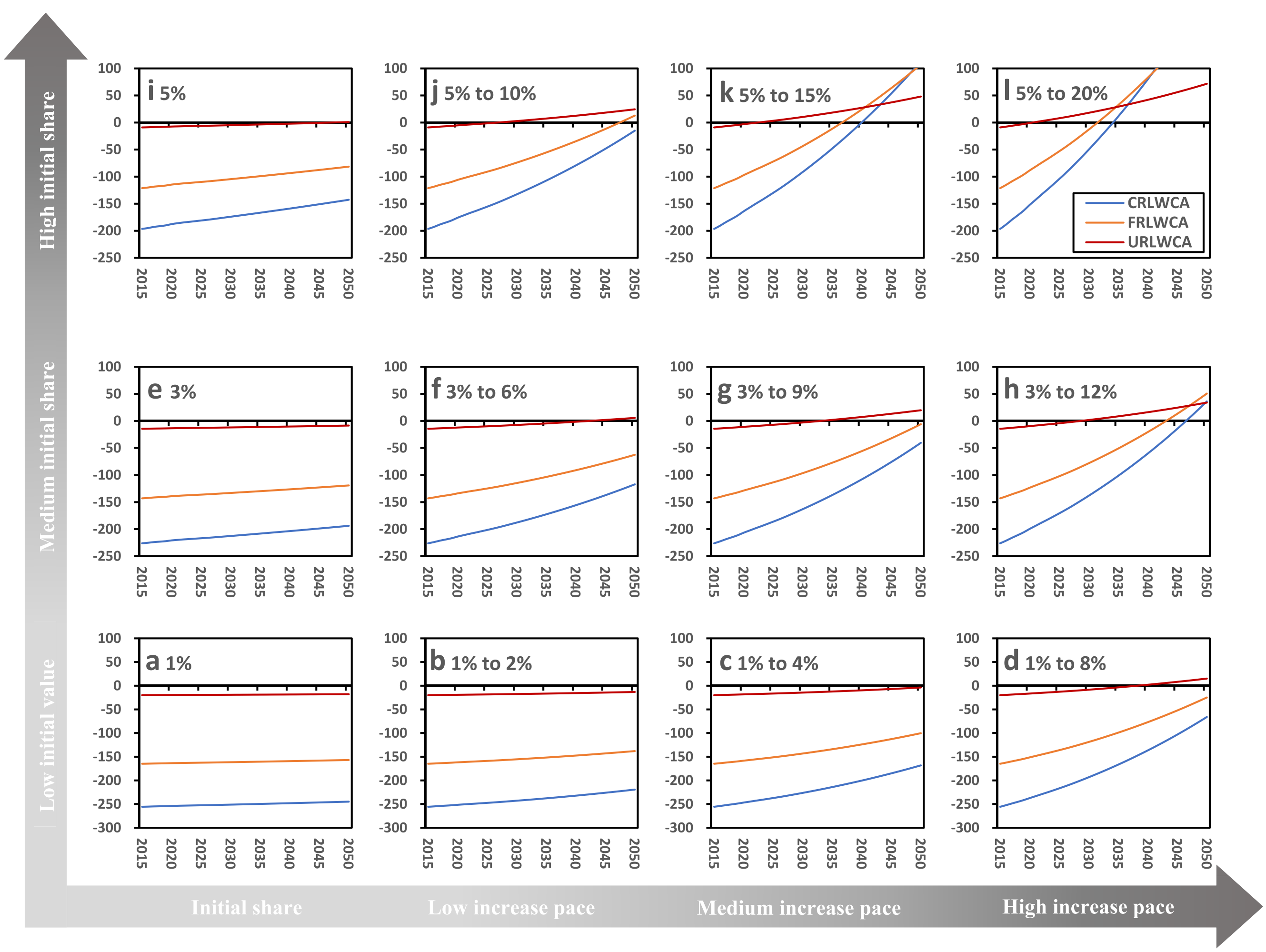

Fig. 11. Supply-demand condition of CRLWCA, FRLWCA, and URLWCA in Kt. Note: 1) "initial share" means "initial value of the share of lightweight concrete waste to the total concrete waste remains at 1%, 3%, and 5% from 2015 to 2050; in (b), "1%–2%" represents a linear share increase from 1% in 2015 to 2% in 2050; 3) zones above represent surplus of secondary raw materials, zones below 0 represent deficit of secondary raw materials.

though it increases to 8% by 2050, production barely meets the demand for widespread renovation until 2050. In this case, a large amount of virgin expanded clay and sand is produced or imported to replenish the CRLWCA and FRLWCA feedstock. If the initial share increases to 3%, the CRLWCA and FRLWCA supplies can sufficiently support building renovations with PCE-refurbs up to approximately 2045 with a high increase speed. If the share is started at 5% in 2015, the supply of FRLWCA and CRLWCA reach the break-even point by 2035. Finally, the production of URLWCA is barely able to sustain consumption under any of the assumptions. Primary sand and expanded clay are, therefore, needed to complement FRLWCA and CRLWCA by 2035 at the latest.

4.4. Implications of this study

4.4.1. Constraints and opportunities of CDW management in the Netherlands

The EU has enacted a series of relevant directives on CDW management and energy efficiency. For example, the Waste Framework Directive (2008/98/EC) sets a 70% target for CWD recovery for EU member states (EC, 2008); the COM (2011) 571 aims to promote resource efficiency during the construction and renovation of buildings (EC, 2011); and the Energy Performance of Buildings Directive (EPBD, 2002/91/EC) (EC, 2002) and Energy Efficiency Directive (EC, 2012/27/EU) (EC, 2012) request member states to employ cost-effective energy renovation measures to promote the energy performance of new and old buildings.

The residential building stock in the Netherlands is relatively poorly insulated and obsolete; approximately half the building stock was constructed between the 1950s and the 1970s—before minimum energy performance requirements were introduced in 1995 (Staniaszek, 2015). In the Energy Agreement for Sustainable Growth (SER, 2013), the Netherlands committed to achieving the ambitious goal of a carbon-neutral built environment by 2050. To support the EU's response to the Paris Climate Agreement, the Government of the Netherlands (2019) enacted a national climate agreement to achieve a 49% mitigation in national carbon emissions by 2030. Thus, an additional reduction of 3.4 Mt of greenhouse gas is required by 2030, and the Netherlands even called for increasing the European target to 55% by 2030. By 2050, the Netherlands is expected to achieve carbon-neutral status (EZK, 2019), setting up a significantly limited carbon budget for the building sector.

For decades, the Netherlands has exceeded the EU target of 70% CDW management but upgrading the practice of road backfilling to high value-added recycling is urgently needed. Due to the topography of the Netherlands, domestic extraction of large quantities of stony mineral resources is not possible. Raw materials for the production of concrete, such as sand and gravel, are, therefore, must be imported and—in the future—recycled domestically. The Dutch government has outlined the goal for a circular economy in the Netherlands by 2050 (Dijksma and Kamp, 2016), involving a 50% reduction in raw material use by 2030 and a fully circular economy by 2050. Therefore, to transition to a fully circular built environment, it is crucial to close the loop of the construction material supply chain, especially emerging materials used in energy renovation.

Prefabrication has been identified as a reliable solution for reducing CDW (Tam et al., 2006); waste concrete can be reduced by 52%–60% as prefabricated products are cast off-site (Tam et al., 2005). Prefabrication also contributes to other on-site benefits, such as improved quality control, tidier and safer working environments, and improved environmental performance (Jaillon et al., 2009). According to the estimation of our model, approximately 8 million m^2 and 17 million m^2 of dwellings are to be constructed and renovated per annum. Therefore, the proposed PCE system presents a promising solution to upgrading the treatment of CDW, waste reduction, and energy renovation. The practice of prefabricating buildings is well established in the Netherlands, with prefabricated elements used in over half (55%) of all Dutch construction projects in 2016 (de Gruijl, 2018). This lays a solid technical foundation for the implementation of the PCE system.

4.4.2. Influence of the density and typology of concrete on mass estimation

Concrete production is the main engine for rapid urbanization. The EU directive of resource efficiency opportunities in the building sector (COM/2014/0445) suggests that concrete waste should be a focal point for CDW management (EC, 2014b). Indeed, the literature review in Table 1 shows that concrete waste management is a significant topic for MFA studies.

In general, the concrete in MFA studies is modeled as normal-weight concrete. In this study, normal-weight siliceous concrete and lightweight aggregate concrete were considered to represent normal-weight concrete and lightweight concrete, respectively. The normal-weight concrete includes other types of concrete, such as limestone concrete, which employs different formulations compared to siliceous concrete. Lightweight concrete can be categorized as lightweight aggregate concrete, foamed concrete, and autoclaved aerated concrete. Despite this diverse typology, the density of concrete is the key factor that could influence MFA because material flows are derived from physical mass data. A concrete waste intensity $K^{(d)}_{concrete} = 902$ kg/m^2 was applied to estimate the generation of normal-weight concrete. Because the waste intensity for lightweight concrete is unavailable, we simplified the estimation of lightweight concrete waste by assuming a share of 1%.

The densities of normal-weight concrete and lightweight concrete used in our analysis were 2089 kg/m^3 and 1963 kg/m^3, respectively. Assuming 1% of lightweight concrete waste by weight, the difference in the mass of gross concrete waste is approximately 2 Kt by 2030; if concrete waste comprises 1% of ultra-lightweight concrete (500 kg/m^3), the mass difference is 28 Kt over the same timeframe. With the gradual prevalence of lightweight concrete in building energy renovation practices, MFA studies should consider the effect of lightweight concrete on mass estimation.

4.4.3. Whether or not to consider renovation waste

The measurement of the composition and generation of CDW is a longstanding dilemma for MFA studies. The generation of renovation waste in particular is relatively difficult to estimate due to diverse retrofitting options, such as external insulation systems, cladding systems, and ventilated façade systems (Villoria Sáez et al., 2018) as well as different levels of renovation, i.e., minor, moderate, deep, and nearly zero-energy building levels (Economidou, 2011). Thus, most of the MFA studies summarized in Table 1 do not consider waste from building renovation. Table 3 provides some examples of waste intensity for the renovation of residential buildings in different regions. In more developed areas, the amount of renovation waste is growing rapidly (Cheng and Ma, 2013). For instance, renovation waste accounts for 29% of the gross CDW by weight in Norway (Bergsdal et al., 2008), and its intensity can reach up to 300 kg/m^2, which considerably exceeds the intensity of construction waste (41 kg/m^2 in this study). In developing countries such as China, renovation waste amounts to less than 1% of gross CDW (Ding et al., 2019b), and intensity could be lowered to 20 kg/m^2. The estimation of renovation waste based on construction area, living area, and useful area can also yield differing results (Coelho and De Brito, 2011).

We assumed that the Netherlands will undergo large-scale

Table 3
Examples of waste intensity for the renovation of residential buildings.

Literature	Location	Amount [kg/m^2]	Remark
Bergsdal et al. (2008)	Norway	60.13−89.47	Residential building
Thorpe (2008); Villoria Sáez et al., 2018	UK	147.84	Residential building, estimation based on volume (m^3) of waste generated per 100 m^2
Villoria Sáez et al., 2018	Spain	2.46−65.24	Residential building
Coelho and De Brito (2011)	Portugal	347.3	Residential building, estimation based on a gross construction area
Mália et al. (2013)	Portugal	28−397	Residential building
Cochran et al. (2007)	USA	43.70−82.00	Residential building
Ding et al. (2019a)	China	15.65−25.98	Residential building
Ding et al. (2019b)	China	21.05	Residential building

renovation, with more than 50% of the current stock (based on 2015 data) to be refurbished. Therefore, renovation waste was considered in the MFA model. The amounts of construction waste, demolition waste, and renovation are presented in Fig. 12. Overall, the amount of renovation waste exceeds the amount of construction waste. It is noteworthy that we only estimated the renovation waste from the implementation of the proposed PCE cladding technology; deeper renovation is expected to yield more renovation waste. Moreover, we only estimated the wastes that can be incorporated into the PCEs, namely concrete, insulation, glass, and steel, which account for 77% of CDW by weight (Zhang et al., 2020c); minor waste streams, such as wood, plastic, and paper, are not included. Given the fact that building energy renovation has become a primary pathway towards a carbon-neutral built environment, considering renovation waste in MFA studies offers a more comprehensive means of CDW management.

5. Conclusions

The building sector is considered one of the main drivers of material depletion, waste generation, energy consumption, and greenhouse gas emissions. It is highly important and urgent, therefore, to accelerate the transition toward a carbon-neutral and circular built environment. Ongoing building energy renovation is accompanied by emerging materials such as mineral wool insulation and lightweight concrete, triggering new problems of disposal. This makes it harder to close supply chains in the building sector. The proposed PCE system delivers a potential solution by incorporating CDW into building energy renovations. Here, we

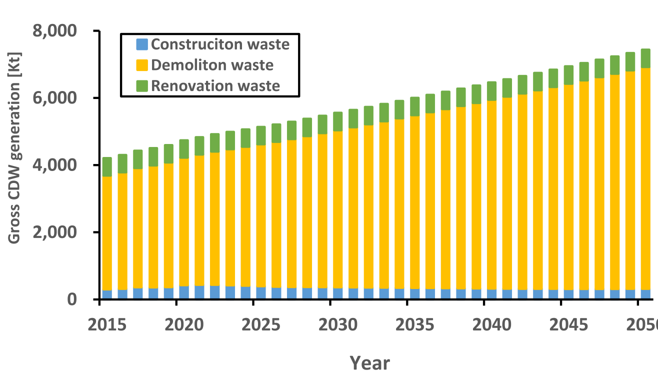

Fig. 12. Generation of construction waste, demolition waste, and renovation waste estimated in the Netherlands for the period 2015−2050. Note: construction waste and demolition waste are estimated based on the share of concrete waste in CDW and the concrete waste intensity.

constructed a prospective top-down stock-driven MFA model to explore the supply-demand condition of associated secondary raw materials for the PCE system for new building construction and existing building renovation in the Netherlands for the period 2015−2050. Compared to previous MFA studies, our model considers the recycling of glass, lightweight concrete, and insulation mineral wool in CDW through an on-site innovative recycling technological system in the context of building energy renovation in the Netherlands.

Our results show that secondary raw materials recycled from normal-weight concrete waste, namely CRSCA, FRSCA, and URSCA, can be sufficiently supplied, even with a large surplus. The reforged steel frames, RGUA, and RFUA required for building construction and renovation can also be sufficiently supplied. However, under the condition that lightweight concrete waste was assumed to account for only 1% of the gross concrete waste, the secondary raw materials CRLWCA, FRLWCA, and URLWCA for new lightweight concrete production are inadequate for supporting manufacturing of the PCE-refurb system. The deficit could be replenished using virgin materials or by importing lightweight concrete waste from neighboring countries. Based on a comparison of the surpluses/deficits of recycled materials to the net import of corresponding virgin materials, we found that the demand for main mineral resources in the Netherlands is highly dependent on imports. Only CRSCA shows potential for offsetting gravel imports assuming conservative imports. The other secondary raw materials do not appear to reduce the import of associated virgin materials.

Using uncertainty analysis, we quantified the influence of variations in (1) construction, demolition, and renovation floor area of each year; (2) concrete waste intensity; and (3) the share of lightweight concrete waste. We used construction, demolition, and renovation rates to compare the uncertainties of construction, demolition, and renovation activities each year from different sources. The results show that the construction and demolition rates are harmonized with historical statistics. The renovation rate is assumed to track the prospective energy renovation planning of the Netherlands and is, therefore, higher than the actual value. Regarding concrete waste intensity, owing to a conservative assumption of concrete waste intensity, the forecast waste concrete stream is relatively lower than the current statistics. Lightweight concrete was modeled with different initial shares in gross concrete waste with an increasing pace, starting from 1%, 3%, and 5% in 2015 and increasing linearly to 8%, 12%, and 20% by 2050, respectively. We found that the production of URLWCA can barely meet the demand under any of these cases, whereas primary sand and cement are still needed for the substitution of FRLWCA and CRLWCA until 2027.

This study has investigated the physical mass link between CDW recycling and secondary material demands in the context of building energy renovation in the Netherlands. However, the associated environmental and financial implications remain unknown. Our previous studies investigated the life-cycle carbon emissions and costs of the PCE system at the building level (Zhang et al, 2020a, 2020b·bib_Zhang_et_al_2020b·bib_Zhang_et_al_2020a). In the future, we aim to scale-up the life cycle environmental and economic benefits of the proposed PCE system for energy renovation at a regional level.

CRediT authorship contribution statement

Chunbo Zhang: Conceptualization, Methodology, Software, Investigation, Writing – original draft, Formal analysis. **Mingming Hu:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Benjamin Sprecher:** Validation, Writing – review & editing. **Xining Yang:** Software, Methodology, Validation, Data curation. **Xiaoyang Zhong:** Methodology, Software, Writing – review & editing, Validation. **Chen Li:** Writing – review & editing, Validation. **Arnold Tukker:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.126835.

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