A spatio-temporal Life Cycle Assessment framework for building renovation scenarios at the urban scale

Alessio Mastrucci[1,2]*, Antonino Marvuglia[1], Enrico Benetto[1], Ulrich Leopold[1]

[1] Luxembourg Institute of Science and Technology (LIST) 5, Avenue des Hauts-Fourneaux L-4362 Esch-sur-Alzette (Luxembourg)

[2] International Institute for Applied Systems Analysis (IIASA), Energy Program (ENE), Schlossplatz 1, A-2361 Laxenburg, Austria

Abstract

Reducing the energy consumption of buildings is a priority for carbon emissions mitigation in urban areas. Building stock energy models have been developed to support decisions of public authorities in renovation strategies. However, the burdens of renovation interventions and their temporal distribution are mostly overlooked, leading to potential overestimation of environmental benefits. Life Cycle Assessment (LCA) provides a holistic estimation of environmental impacts, but further developments are needed to correctly consider spatio-temporal aspects.

We propose a spatio-temporal LCA framework to assess renovation scenarios of urban housing stocks, integrating: 1) a geospatial building-by-building stock model, 2) energy demand modelling, 3) product-based LCA, and 4) a scenario generator. Temporal aspects are considered both in the lifecycle inventory and the lifecycle impact assessment phases, by accounting for the evolution of the existing housing stock and applying time-adjusted carbon footprint calculation.

We apply the framework for the carbon footprint assessment of housing renovation in Esch-sur-Alzette (Luxembourg). Results show that the renovation stage represents 4% to 16% of the carbon footprint in the residual service life of existing buildings, respectively after conventional or advanced renovations. Under current renovation rates, the carbon footprint reduction would be limited to 3-4% by 2030. Pushing renovation rates to 3%, enables carbon reductions up to 28% by 2030 when combined with advanced renovations. Carbon reductions in the operational stage of buildings are offset by 8-9% due to the impacts of renovation. Using time-adjusted emissions, results in higher weight for the renovation stage and slightly lower benefits for renovation.

Keywords

Building stock renovation; Urban energy planning; Life Cycle Assessment; Geographical Information Systems; Carbon footprint; Time-adjusted emission accounting

1. Introduction

The building sector is responsible for major environmental impact, mostly due to space heating, domestic hot water heating and construction works [1]. The final energy consumption of buildings represents 40% of the total energy consumption in the European Union (EU) [2] and represents a key sector for achieving carbon mitigation objectives [3]. A wide legislative framework was therefore developed to foster reductions in buildings energy consumption in the EU [2] [4], where retrofitting existing buildings represents one of the most effective strategies [5].

Due to the growing degree of urbanization – expected to attain 85.9% in 2050 in developed countries [6] – cities play a central role in the design, implementation and monitoring of sustainable plans. They are in the need of reliable tools to assess the effect of policies on the carbon mitigation of the building sector. In recent times, significant efforts have been put on the development of building stock energy models to assess energy demand and energy saving potentials of building renovations [7–13].

Although the environmental impact of conventional buildings is dominated by the operational stage [14], the modern shift towards low-energy and zero-energy buildings resulted in an increased weight of the environmental impacts for the production-construction and renovation stages [3,15]. Omitting these stages might result in overestimating the potential environmental benefits of renovation [16], especially for scenarios based on deeper interventions. Therefore, a holistic assessment of energy demand, resources durability and environmental performance of building stocks at larger spatio-temporal scales is increasingly needed for decision support in sustainable urban planning [10,17–20].

Life Cycle Assessment (LCA) has been broadly used to quantify the environmental impacts of buildings considering their entire life cycle [14,21–24]. However, the upper levels in the hierarchy of the built environment (i.e. urban blocks, districts, cities, and larger urban agglomerations) have been less investigated [25]. The extension of LCA to the urban scale implies methodological and operational challenges [17], for which LCA standards or guidelines are currently missing.

To conduct a comprehensive assessment of the potential environmental impacts of buildings and mitigation scenarios at the urban scale, building stock models, energy demand models and LCA need to be combined. Few recent studies have expanded the scope of LCA from single buildings to urban building stocks using a bottom-up approach [17,25]. Yet, open issues remain for the representation of spatial and temporal aspects related to the building stock.

The time-related aspects concern the dynamics of the stock in terms of size, composition and level of renovation [26]. While most of the existing studies on urban building stocks focused on the theoretical energy and greenhouse gases (GHG) emissions reduction potential, accounting for the stock dynamics is key for developing more realistic renovation scenarios [17]. As regards the environmental impact assessment, conventional (static) LCA introduces a bias as emissions released at different times are summed up as if they were emitted instantaneously and constant characterization factors (CFs) at a given time horizon (typically

100 years) are applied [27]. Methods based on time-horizon-dependent CFs enable accounting for the actual difference in time between the emission releases and for the chosen end-time [28].

Regarding the spatial representation of urban building stocks, different approaches and levels of granularity have been used in literature, from using building archetypes to represent specific building cohorts and location areas (*archetypes* approach) [29–31] to a more advanced use of Geographical Information Systems (GIS) for data acquisition and processing at the level of individual buildings (*building-by-building* approach) [32,33]. The *archetypes* approach has been widely used as it enables an easy building stock characterization and scenarios creation [34]. However, it implies many assumptions, possibly oversimplifications, and often lacks the spatial dimension, which could be enhanced by GIS [35]. A complete and automatic information flow between GIS, LCA, and building energy model platforms is largely missing and could support an improved representation of spatial aspects.

We propose a spatio-temporal LCA framework of housing stock renovation scenarios at the urban scale. We use a GIS-based building-by-building approach and account for the variability of geometry, building envelope and technical systems across an entire city. Temporal aspects are considered both in the life cycle inventory (LCI) and impact assessment (LCIA) phases, respectively by considering the evolution of the existing housing stock and by applying time-adjusted carbon footprint calculation [27].

In this paper, we apply the LCA framework limited to the carbon footprint assessment. The complete methodology includes the following steps: 1) Characterization of the urban housing stock using a building-by-building approach; 2) Development of scenarios for building renovation; 3) Energy analysis of space heating and domestic hot water requirements; 4) Carbon footprint assessment of housing renovation. We tested the methodology for the housing stock of Esch-sur-Alzette (Luxembourg), consisting of approximately 13'000 housing units. In the following sections, we first discuss the state of the art in building stock modelling (section 2), introduce the methods and datasets (section 3), and present the results (section 4). We then discuss the outcomes of this study towards improving consideration of spatial and temporal aspects in building stock modelling (section 5) and we conclude (section 6).

2. State of the art

The following paragraphs discuss the state of the art on building stock modelling, accounting of the spatio-temporal dimensions. The results of the literature review are summarized in Table 1. An extended state of the art is available in the Supplementary Material (section SM1).

Table 1 Summary of the literature review on urban building stock modelling.

Element	Components/ Aspects	Use	Approaches	Gaps and opportunities

Building stock modelling	Energy model	Estimate the building energy demand.	Statistical, engineering, hybrid[7–12].	Existing models mostly focused on operational energy, but overlooked broader life-cycle impacts [3,10,15–17].
	LCA	Assess environmental impacts along the life cycle of buildings.	Process-based LCA, hybrid-LCA [17,25,32,36].	Potential to represent the broader environmental implications of energy savings measures [14,21,22]. Methodological advancements needed for LCA upscaling and integration in building stock models [17,25].
	Building stock aggregation	Quantify volume and characteristics of the stock.	Archetypes, samples, building-by-building [7,17].	Archetypes commonly used at the urban scale [34]. Building-by-building more data-intense but provides more accurate results [15,17,33,36].
Temporal dimension	Building stock evolution model	Represent the building stock dynamics.	Accounting, static, dynamic [32,37–42]. Dynamic can be activity- or stock-driven [37,38,43–48].	Only few studies considered the temporality of renovation at the urban scale [49]. Potential to use stock dynamics models for stock evolution scenarios [37–40].
	Time-dependent environmental impact accounting	Accounting of emissions over time.	Static, Time-adjusted characterization factors [27,50]	Emission timing has been overlooked in traditional LCA, with potential results distortion [27,50–52].
Spatial dimension		Accounting of spatial aspects.	Use of regional archetypes [29–31], spatial data [53–55], GIS integration [32,33,35,56,57].	Potential to include spatial constraints and hotspots identification [33,49,58,59]. Methodological advancement on GIS-LCA integration is needed [60,61]. GIS integration can support efficient spatial information management and processing and improve model accuracy [15,33,36,56,57,60].

2.1. Building stock modelling

Building stock energy models estimate the energy demand and the technical and economic effects of carbon mitigation strategies to support policies at sectoral level [7,8,10]. Building stock models can be broadly divided into *top-down* and *bottom-up*. The former aim at finding correlations between the national energy consumption and socio-economic or socio-technical drivers [11]. In the latter, the energy demand is extrapolated from individual buildings (or groups of buildings) to the entire building stock. Bottom-up building stock models typically consist of three main components [17]: an *energy demand model*, to determine the energy use of the building stock and potential savings after implementing energy savings measures; an *LCA model* (optional) to assess the broader environmental impacts of building activities and operations [15,32,36]; and a *building stock aggregation model*, to aggregate results at the stock level and quantify the volume and characteristics of the stock, in the baseline and along future scenarios.

Bottom-up building energy demand models can be broadly divided into: *statistical*, *engineering* (or *physically-based*), and *hybrid models* [8,12,13]. Physically-based methods are broadly used for their ability to account for the impact of new technologies [7].

LCA enables a more comprehensive analysis of the environmental impacts related to building operation and activities, including construction and renovation [14,21,22]. LCA approaches include process-based and hybrid LCA [25]. Energy demand and environmental impacts are commonly calculated for a set of building archetypes (*archetypes* approach) or a representative sample of the building stock (*samples* approach), and results aggregated at the stock level using some dimensions, e.g. the floor surface area per group of buildings. An alternative approach (*building-by-building*) consists in modelling all buildings in the stock. While mostly used at the neighbourhood or small city level, the increasing amount of building databases (especially GIS) enables the application of this approach at larger scales, albeit at the cost of greater data requirements and computation loads [17]. Nevertheless, the building-by-building approach enables better integration with GIS data, model refinement, and LCA applications where the physical dimension of buildings becomes even more important (e.g. to quantify the amount of resources in building operations).

2.2. Temporal dimension

Two time-related aspects are key in the LCA of building stocks scenarios: the evolution of the building stock and consequent variations in the LCI; and the accounting of environmental impacts, and in particular GHG emissions, over time in the LCIA. From the time-dependency point of view, building stock models can be classified into three types: *accounting*, *quasi-stationary* or *static* and *dynamic* [39,40]. Accounting models quantify the stock size and composition, and the associated material or energy flows, without analysing the drivers of the stock development and energy use. Explaining the stock size, composition, and energy consumption starting from specific drivers, is instead the aim of the other two types of models. Static models focus on the stock at a precise moment in time [30,32,42], typically a single year.

Dynamic models try to follow the evolution of the building stock in time, over multiple years. Dynamic models can be further divided into: *input-driven* or *activity-driven*, and *stock-driven* [39]. Activity-driven models [39,43–46] generally describe the evolution of the building stock using construction and demolition rates (mostly based on historical time series) as drivers. Stock-driven models [37,38] use the service demand/provision concept [47], which relies on time-dependant factors such as population and preference in size and type of buildings, and mass balance equations to model construction activities. The temporality of refurbishment operations has been assessed for national building stocks using probability functions to describe renovation cycles [46,48] or combined material flow analysis (MFA), LCA, and optimisation methods to identify and prioritize buildings with the highest energy saving potential [38]. At the urban scale, the temporality of renovation has been mostly overlooked, except for the application of fixed renovation rates [49]. We adopt a similar approach in our study and analyse the sensitivity to different renovation rates. More sophisticated methods for accounting the building stock evolution and renovation cycles can be coupled to the framework and will be the object of future developments.

Emission timing has been overlooked in traditional LCA, as GHG emissions are summed together despite of different timings. Thus, a distortion occurs as the time horizon for emissions is predetermined, e.g. to 100 years, but the end-points of analysis are different as emissions are released at different time. Alternative approaches based on time-adjusted CFs have been developed to compare GHG emissions using a fixed end point [27,50]. These approaches favour emissions released on a later moment, for which the time horizon is shorter [52]. A full dynamic LCA approach has been proposed [62] and demonstrated [63], which however would require the integration of the complete building stock dynamics, which goes beyond the scope of the present study. In this study, having an explicit representation of the building stock dynamics and renovation operations enables accounting for impacts occurring over time, and using time-adjusted CFs for GHG emissions. Therefore, we apply here both static and time-adjusted CFs and compare the outcomes in order to derive some useful recommendations for decision support.

2.3. Spatial dimension

Explicitly accounting for the spatial dimension in building stock modelling allows refining the building data, identifying hotspots, and considering spatial constraints (e.g. availability of infrastructures, local intervention constraints, historical buildings, etc.) [33,49,58,59]. With GIS, it is possible to manage and process large spatial datasets, enabling building-by-building simulations. A fully-fledged coupling between LCA and GIS has been realised in some applications, however consensus is still missing on their integration and methodological advancements are further needed [61][60]. GIS is often used to retrieve buildings data, such as floor area, number of storeys, vintage or building type, from existing datasets or to visualize results [17,56,57]. LiDAR (Light Detection and Ranging) data [53,54,64], urban registries data [35,57], and open spatial datasets [55] can provide more detailed information about the building geometry and characteristics. This, in turn, enables accurate estimations of the materials required for renovation operations and related impact [15,33,36], and provide relevant input data for building energy models and LCA. Further developments are still needed to establish more complete and automatic information flows between GIS, LCA and building energy model platforms.

3. Material and methods

3.1. Methods overview

Figure 1 provides an overview of the generic framework for the LCA of building renovation at the urban scale. The workflow is based on the following four steps. The first step consists in the building stock characterization: information on building geometry, building envelope, technical systems and building operations are associated to individual buildings in the stock from a range of sources, including GIS data, statistics, building libraries, regulations and standards. Information not directly available at the building level may be distributed across the stock using a probabilistic approach (e.g. random distribution of past renovation interventions based on statistics [48,65]). Second, renovation scenarios are defined and future renovations distributed across the building stock based on the estimated renovation rates. Third, the final energy demand for space heating and domestic hot water, is calculated for every building, in the current state and after renovation. Finally, LCA is performed to assess the environmental impact of the building stock along the renovation scenarios. Impacts are calculated at the building level for both buildings operation and renovation and then aggregated at the stock level.

This framework is mainly implemented in R [66], including the stock characterization module, the scenarios generator, the energy demand model, and the LCA module. A connection to a spatio-temporal database in PostgreSQL[67] and PostGIS [68] was set up for improved data transfer and storage. We use QGIS [69] and GRASS GIS [70] for spatial data processing and spatial results visualization. The methodology is adaptable to other contexts when minimum data requirements are satisfied (see Supplementary Material, SM2).

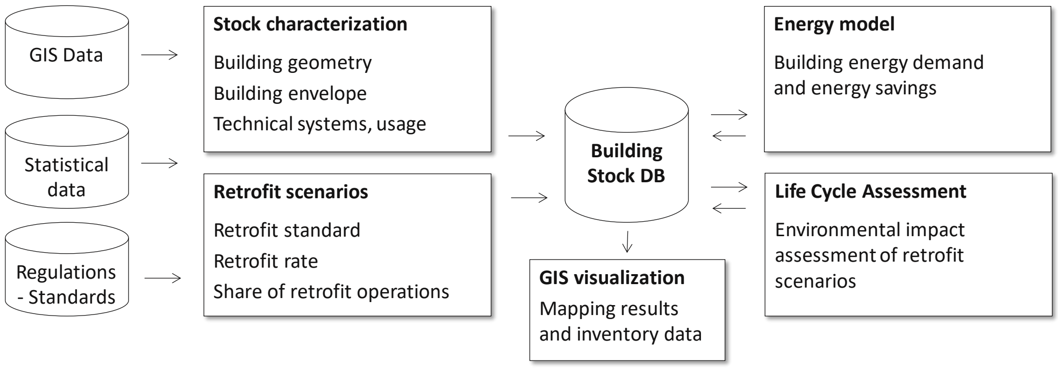

Figure 1 Overview of the methodology.

3.2. Case study

Luxembourg set up the target of 40% GHG emissions reduction by 2030 based on the level of emissions in 2005 [71]. Improving the energy efficiency of existing buildings is a key strategy, supported by the energy efficiency action plan [72] and the national renovation strategy [73]. Here, we estimate the carbon footprint reduction potential for renovating the existing housing stock of Esch-sur-Alzette, second most-populated municipality in Luxembourg (32,600 inhabitants in 2014, 35,400 in 2019 [74]) and develop scenarios until 2030 for decision support in renovation strategies.

3.2.1. Building stock description

The housing stock of Esch-sur-Alzette, composed of 6407 buildings in 2014, is classified into: Single-Family Houses (SFH), further divided into Detached Houses (DH) and Row Houses (RH) to account for their different geometry and energy performance [75,76]; and Multi-Family Houses (MFH), including residential and mixed-function buildings (residential and other functions).

Two-thirds of the buildings are SFH (mainly RH) although they represent only 44.4% of the floor surface, being of smaller size than MFH [54]. More than half of the housing stock was built before 1949, following major developments in steel industry and mining activities. Another quarter of the stock dates back to the period 1949-68. The renovation potential is therefore high due to the vintage of the stock and relatively low share of refurbished buildings. Prevailing construction systems include masonry for SFH and concrete framing for MFH. Heating systems are mainly gas or oil boilers. A district heating network serves a small portion of the housing stock. See Supplementary Material SM3 for more details on the housing stock characteristics.

3.2.2. Dataset

The main geospatial dataset was provided by the Municipality and includes LiDAR and building footprints data. A Digital Surface Model (DSM) and Digital Terrain Model (DTM) were generated from the LiDAR data to obtain information on the height of buildings [54]. The building footprint vector file contains a series of attributes at the building level, including year of construction, housing type, presence of attic and basement, and the number of occupants.

We retrieved additional input data, including building envelope characteristics, technical systems, occupants' behaviour (set point temperatures and heating schedules) and climatic data, from a range of sources, as described hereafter. Thermal properties of materials were obtained from the standard DIN 4108-4:2013 [77]. U-values of existing buildings were set based on national data [78]. Data on renovation standards were obtained from national regulations [79–81]. Input data on technical systems, share of renovation operations, and renovation rate were defined based on national statistics [74], technical standards, regulations [79,80], previous studies [54,82] and interviews with local experts. Climatic data were obtained from the national regulation on the building energy performance [79,80]. We used the database Ecoinvent 3.4 [83] to build the background LCI of renovation interventions, materials and building operations (see Supplementary Material, sections SM6-7, for detailed LCI data and LCIA results).

3.3. Building stock characterization

We distinguish between the building geometry for the geospatial pre-processing and the building envelope to characterise the building stock for the energy analysis. Technical systems are described to characterise the heat consumption patterns.

3.3.1. Building geometry

We estimate the main geometrical features of individual georeferenced buildings across the city by systematically processing the available GIS data (DSM, DTM and building footprints vector file). Specific algorithms for geospatial processing and data analysis developed in GRASS GIS [70] are applied here based on a previous study [54], to which we forward the reader for further details. Output of the GIS processing include average building height, ground floor and roof area, building gross volume, floor surface area, area of external walls, and walls in common with adjacent buildings. Key results for different housing types and periods of construction are reported in the Supplementary Material (section SM3).

3.3.1. Building envelope

The building envelope characteristics are identified across the building stock based on the housing type and period of construction of each building. We set U-values (Table 2) consistent with national reference values for existing buildings [78]. U-values for older buildings were adapted based on the recommendations of other studies [84] and a building period was added for constructions erected after 2008, when a new thermal regulation came into force in Luxembourg.

The current renovation state of the buildings was also considered and past renovations distributed across the stock based on a stochastic approach, due to the lack of more precise information. The share of renovated buildings was estimated, for every housing type and period of construction, based on the list of granted construction and renovation authorisations provided by the municipality, national statistics [85], and local experts' knowledge (see Supplementary Material, section SM3). The U-values of buildings concerned by past renovations were then updated based on the values for the periods 1995-2007 and after 2007 (Table 2).

3.3.2. Technical systems

Five types of heating system are considered in this study: four systems with gas and oil boilers (either conventional or condensing), and district heating network. Other system types and energy carriers have not been considered due to their very low share in the housing stock of Esch-sur-Alzette. The presence of heating district network was considered, by spatially identifying the perimeter of the served district in GIS. Boiler of different types were distributed across the stock based on the national household survey data [74] and previous studies, being the information on individual heating systems not available. A set-point of 20°C was considered for space heating [79,80].

Table 2 U-values of opaque envelope structures for different periods of construction and housing types (single-family houses SFH and multi-family houses MFH). Source: [78,84] *and authors' estimation.*

Period of construction	U-values *(W/m²K)*				
	External walls	Roof (massive)	Ground floor	Windows (SFH)	Windows (MFH)
<1949	1.1	1.4	1.2	2.7	3.0
1949-1957	1.1	1.4	1.5	2.7	3.0
1958-1968	1.1	1.4	1.0	2.7	3.0
1969-1978	1.0	0.6	1.0	2.7	3.0
1979-1983	0.8	0.5	0.8	2.7	3.0
1984-1994	0.6	0.4	0.6	2.7	3.0
1995-2007	0.5	0.3	0.6	1.6	1.9
>2007	0.32	0.25	0.32	1.6	1.9

3.4. Renovation scenarios

We developed a set of four renovation scenarios by combining two levels of intervention – corresponding to different energy-efficiency standards for renovations - and two sets of renovation rates.

Renovation standards are defined by two levels of intervention (Table 3): *Standard S1* is based on the current U-value limits for new buildings contained in the national energy performance regulation [79,80]; *Standard* S2 represents an improved level of performance according to the highest standard of performance in the national regulation to access incentives for the renovation of existing buildings [81]. The considered renovation measures include roof and external wall insulation, windows replacement and replacement of standard boilers by condensing boilers. We only simulate complete renovation packages, i.e. all measures are concurrently applied as needed. Geospatial queries of the building database allowed identifying historical buildings with potential constraints for renovation implementation. For buildings erected before 1949 and located in the historical city centre, we conservatively consider renovation standard S1 in all scenarios, no addition of ground floor insulation, and application of internal (instead of external) wall insulation for façade preservation.

Materials and components installed as part of renovations also have influence on the associated environmental impact. We initially assume expanded polystyrene (EPS) panels for envelope insulation and windows with Polyvinyl chloride (PVC) frames for all interventions. We then run a sensitivity analysis by changing the type of insulation material (EPS, extruded polystyrene – XPS –, glass-wool and rock-wool) and window frames (wood, metal or PVC).

Table 3 Renovation standards for the building envelope in the renovation scenarios. Standard S1 corresponds to current requirements in [79,80] *for new residential buildings and Standard S2 to the best standard of performance in* [81] *for existing residential buildings in Luxembourg.*

Building element	U-values *(W/m^2K)* of renovation standards	
	Standard S1	Standard S2
Walls insulation - External	0.32	0.13
Walls insulation - Internal	0.40	-
Roof insulation	0.25	0.10
Ground floor insulation	0.40	0.15
Window replacement	1.50	0.75

We test two yearly renovation rates in this study: a basic rate of 0.5% (R1) reflecting the current situation [75] and an improved rate of 3.0% (R2) in line with the accelerated renovation rates to reach energy efficiency goals assumed by other studies for

Europe [86] and in Luxembourg [71]. Renovation operations were randomly distributed across the stock by applying fixed shares of renovated buildings by housing categories (Table 4), based on current national trends on complete building renovations [85]. Renovations occur in Luxembourg mostly for buildings before 1960 (75% of total renovations) and predominantly on SFHs (almost 70% of the total renovations). The time horizon for the analysis was fixed to 15 years (2015-2030) for mid-term predictions and consistent with the time horizon of emission reduction targets for Luxembourg.

Table 4 Distribution of renovation interventions among the building stock depending on different periods of construction housing types (single-family houses SFH and multi-family houses MFH) in the renovation scenarios.

Period of construction	Share of renovated buildings per housing type *(%)* SFH	MFH	Total
<1919	14.78	6.83	21.61
1919-1945	24.91	9.09	34.00
1946-1960	16.94	3.48	20.42
1961-1970	4.75	2.50	7.25
1971-1980	2.15	1.52	3.67
1981-1990	1.83	1.95	3.78
1991-2000	1.85	2.52	4.37
2001-2015	2.65	2.25	4.90
Total	**69.86**	**30.14**	**100.00**

3.5. Energy demand model

The energy demand model for the housing stock of Esch-sur-Alzette is based on the current national regulation for the energy performance of buildings in Luxembourg [79,80]. The calculation of energy requirements for space heating and domestic hot water is performed in semi-steady state. The monthly energy demand for space heating is calculated using equation (1):

$$Q_{h,M} = Q_{tl,M} + \eta_M \cdot (Q_{s,M} + Q_{i,M}) \qquad (1)$$

where $Q_{h,M}$ is the monthly energy demand for space heating in kWh, $Q_{tl,M}$ is the monthly heat losses for ventilation and transmission in kWh, η_M is dimensionless heat gain utilisation factor, $Q_{s,M}$ and $Q_{i,M}$ are the monthly solar and internal heat gains in kWh. We apply simplifications for existing buildings, in accordance to the national recommendations, regarding thermal bridges, shading calculation, efficiency of heating and domestic hot water systems. We forward the readers to the cited regulations for more details.

3.6. Carbon footprint

We perform a carbon footprint assessment of building stock renovation according to the standards EN 15643-2:2011 [87] and EN 15978:2011 [88] to estimate emission reduction potential along different scenarios. Carbon footprint was chosen because of its relevance for the building sector [15]. Furthermore, it allows comparability with other studies at the urban scale where it is widely used [17]. The environmental impact was calculated on a building-by-building basis and then aggregated at the stock level to estimate: 1) the carbon footprint reduction potential along the residual life cycle of different building categories; and 2) the difference in carbon footprint along different scenarios of building renovation for the existing housing stock of Esch-sur-Alzette in the period 2015-2030.

We run calculations using both traditional emission accounting with fixed CFs (fixed time horizon), and time-dependent CFs for GHG as defined by Kendall [27] (fixed end-point in time and therefore variable time horizon), to show the implications of different modelling choices. In the former, all emissions are accounted with a time horizon of 100 years, regardless of when they occur; therefore, a sliding time window of 100 years is considered (see Figure 3 in [28]). In the latter, the end point of the analysis is fixed at 100 years and time horizons are variable depending on when emissions occur, i.e. emissions released later in time are adjusted to discount the impact beyond the end-point of 100 years (see Supplementary Material, SM4).

The analysis included the following life cycle stages:

1. Renovation stage: production and transportation of building material and components to be installed.
2. Operational stage: energy consumption for space heating and domestic hot water.

The selected functional unit is the residential building stock of the entire city. Results are then rescaled to *1 m^2* of floor surface for the sake of comparability with other studies. The residual service life of buildings was fixed to 30 years, being the median value identified by other studies for buildings in Europe [89].

The building stock characterization and the energy demand calculation steps provide the foreground LCI both at the building and stock level. The inventory for the renovation stage includes the quantity of material to be installed for individual buildings (see also Supplementary Material, section SM6). For opaque elements, we calculate the amount of required insulation material based on the surface of envelope elements (walls, roof and ground floor) of individual buildings and the density and thickness of insulation material required to meet the renovation standard. For transparent elements, the material requirements are calculated based on the window surface of individual buildings. The impacts of transportation are calculated assuming a transportation by lorry and considering a travel distance of 50 km to the building site for inert materials and 100 km for all the other materials [90].

The foreground LCI is spatially explicit, as data are building-specific and geo-referenced using the spatio-temporal database. Temporal aspects are partly accounted in the LCI, as the existing buildings stock changes year by year depending on the uptake of renovations. No temporal or spatial differentiation are currently considered in the background LCI data. In a further study, full temporal differentiation (in the foreground and background inventory) could be investigated using the approach proposed by Turuta-Barna et al [62] and the tool develop by Pigné et al [63].

The carbon footprint calculations are performed using dedicated R algorithms. First, the inventories of unit processes from the database Ecoinvent 3.4 [83] (e.g. one unit of material produced, see Supplementary Material, SM5) are imported into R. Then LCIA is run by using the CFs described above. Finally, results are aggregated at the building level and stock level (see Supplementary Material, section SM6).

4. Results

4.1. Operational energy

4.1.1. Energy use of buildings

Figure 2 shows the distribution of primary energy intensity per floor area unit across the housing stock of Esch-sur-Alzette, per type of housing and period of construction (before 1970, 1970-95, and after 1995). Both vintage and housing type have a significant influence on energy use. Older buildings are characterized by higher energy intensities per floor area unit mostly due to the poor thermal resistance of the envelope. Buildings constructed after 1995 have the lowest energy intensities, because of energy performance improvements driven by the building regulations enforced in that period. The influence of the housing type on energy intensities is twofold. First, the more compact the building shape is, i.e. the lower the volume to surface ratio (such as for RH and especially MFH) is, the lower the heat losses are and the higher the energy performance is. Second, the efficiency of heating systems is higher for apartment blocks. Therefore, MFH have the lowest energy intensities, followed by RH and DH.

The variability of energy intensities within single housing categories provides additional insights. DH have the highest variability in energy intensity, as they are characterized by a wide range of geometries and characteristics. Older SFH tend to have higher variability in energy consumption, due to a variety of refurbishment conditions reflected by the envelope thermal properties. In contrast, MFH have more homogeneous energy intensity values across different vintages, due to a lower share of refurbished buildings.

The results validation showed good agreement of the results against reference and measured data (see Supplementary Material, section SM7) at two different levels: first, we compared energy intensity values to national benchmarks; second, we compared results aggregated at the postcode-level with measured consumption provided by the local energy supply company.

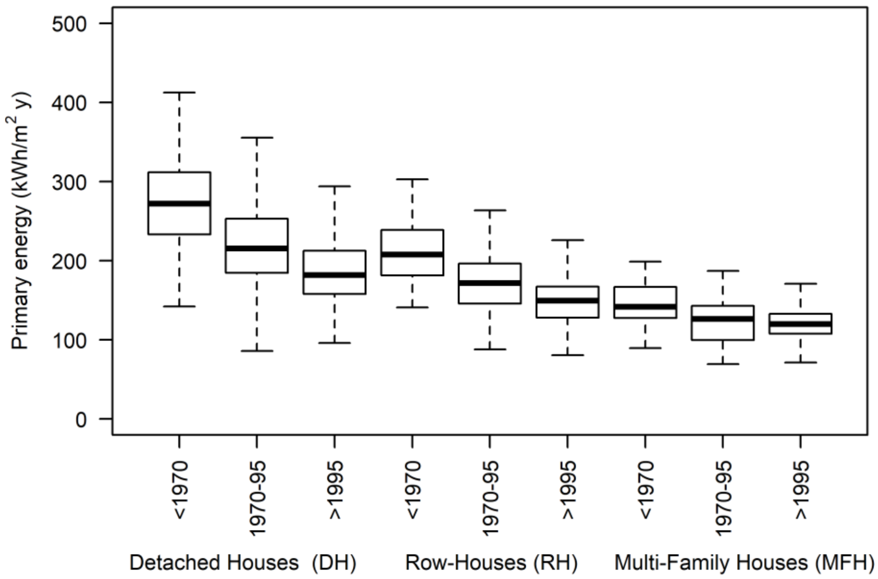

Figure 2 Distribution of the final energy use for space heating and DHW in the housing stock for different housing types and periods of construction

4.1.1. Energy savings potential

Figure 3 shows the total operational energy savings potential by housing type and period of construction for two renovation standards (conventional S1 and advanced S2). The figures show a high energy saving potential for buildings constructed before 1970. Most of these buildings have energy savings in the range of 50-70% and 70-80% by implementing renovation standard S1 and S2, respectively. Houses built after 1970 have lower energy savings potential, due to their improved thermal characteristics (Table 2). Switching from standard S1 to S2 entails higher operational energy savings potential and a tighter distribution. Regarding the housing typology, RH and MFH, especially those built before 1970, embed the highest share of total energy savings potential, due to their broad distribution across Esch-sur-Alzette. Despite their higher energy intensity, DH have lower total energy savings potential, due to a limited presence in the city.

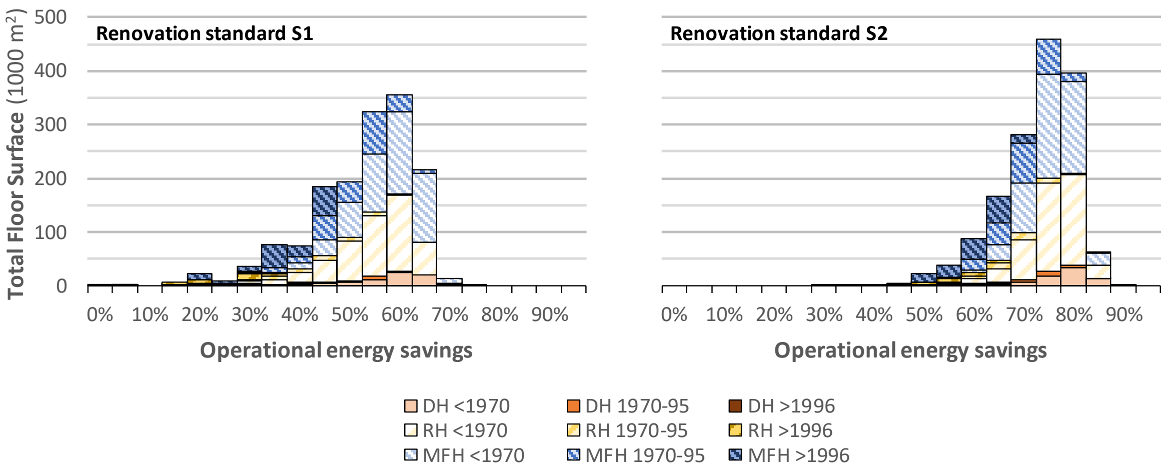

Figure 3 Total energy savings potential for renovation of residential buildings in Esch-sur-Alzette for renovation standard conventional (S1, left panel) and advanced (S2, right panel), by housing type (detached houses DH, row houses RH and multi-family houses MFH) and period of construction.

4.2. Carbon Footprint

4.2.1. Impact mitigation potential

Figure 4 reports the carbon footprint intensity per floor surface unit over the residual lifetime of different types of housing and periods of construction without and with the implementation of renovation measures (assumed to be implemented as of now). Comparing results using fixed (Figure 4-a) and variable time horizons (Figure 4-b) reveals important differences. Accounting for temporality (i.e. considering a fixed end-point for all the emissions) leads to a lower impact of the operational stage. The reason is that the operational stage spans over a long time (i.e. until matching the 100 years end-time of the analysis), whereas renovation interventions are punctual. Whilst the operational stage is dominant in the residual service life of renovated building, the renovation stage accounts on average for 4-5% of the total impact after implementing renovation with standard S1 using fixed time horizons for the LCIA, and up to 6-8% with variable time horizons. The contribution of renovation rises to 11-16% with standard S2 and fixed time horizons and up to 16-22% with variable time horizon, due to the thicker insulation layer and more impact-intensive windows required to meet this standard. The impacts of renovation are the highest for DH and RH built before 1970 (which required thicker insulation, larger envelope surface area per floor unit to insulate and more frequent heating system replacements) and the lowest for MFH built after 1995.

Similarly, the potential reductions in operational impact intensity vary depending on the housing type, vintage and selected renovation standard. Buildings constructed before 1970 have the highest net average impact intensity reduction potential, in the range (depending on the housing type) of 51-56% and 67-70%, for S1 and S2 respectively (fixed time horizons). DH have the highest impact intensities but also the highest reduction potential, while MFH have the lowest. The potential for GWP intensity reduction decreases for buildings constructed after 1970 and especially after 1995. Neglecting the impacts of renovation implies a non-negligible overestimation of impact reduction potential in the range of 4-17% and 7-28% respectively with fixed and variable time horizons, depending on the housing category.

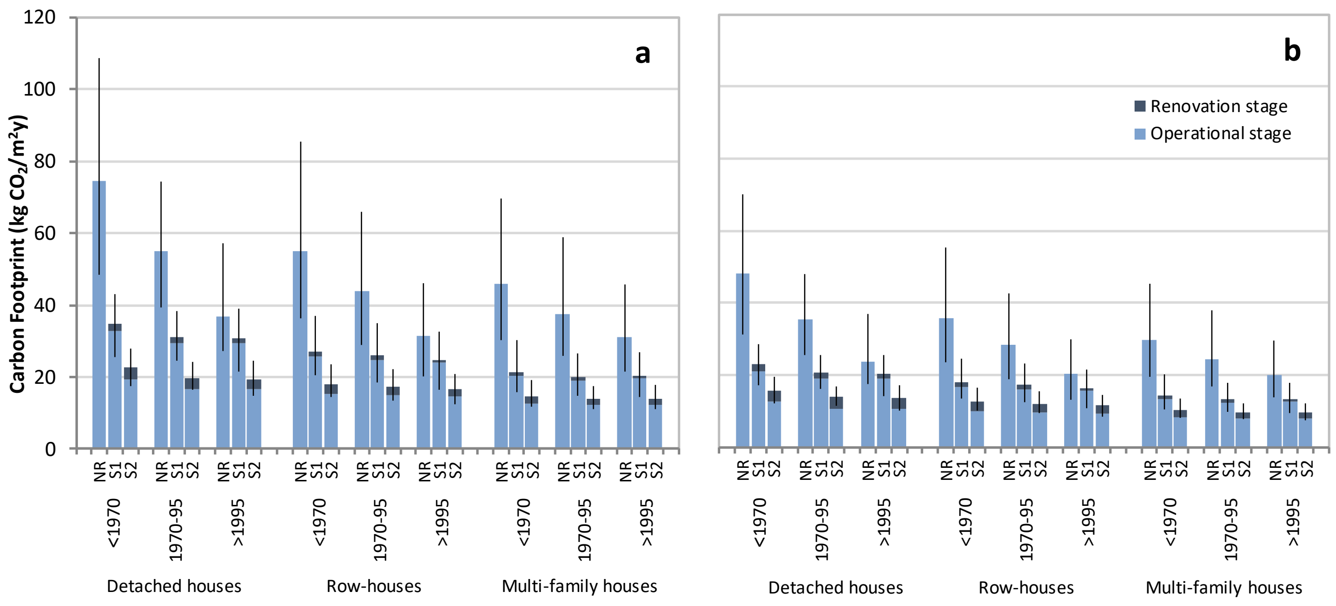

Figure 4 Carbon footprint along the residual life-cycle of residential buildings in Esch-sur-Alzette per floor area unit per housing type and period of construction without renovation (NR) and with different renovation standards (S1 and S2). Bars indicate median values; whiskers indicate 5% and 95% quantiles. Results are shown for calculation with fixed (a) and time-dependent (b) characterization factors.

4.2.2. Impact of the renovation stage

The breakdown of average carbon footprint between different renovation measures (envelope insulation, windows replacement and boiler replacement) is reported in Figure 5 by housing type, period of construction, and renovation standard. The envelope measures (insulation and windows replacement) entail a large share of the environmental impacts, and vary significantly depending on the housing type and period of construction, as a function of the envelope surface extent (higher for DH and lower for MFH) and current thermal properties of the envelope (worse for older buildings, requiring thicker panels for insulation). When the renovation standard S1 is implemented, the share of carbon footprint associated with windows replacement is the highest, ranging from 51% to 70% of the total. Advancing to renovation standard S2 requires a much thicker insulation layer, increasing the amount of material required and associated carbon footprint, while the impact for producing windows with better thermal performance increases only marginally. As a result, the impact associated with insulation dominates when implementing renovation standard S2, with a share of 58-63%. Boiler replacement represents a smaller share of the total impact for renovation. Nevertheless, these numbers are averages across building categories and depend on the number of boiler replacements required.

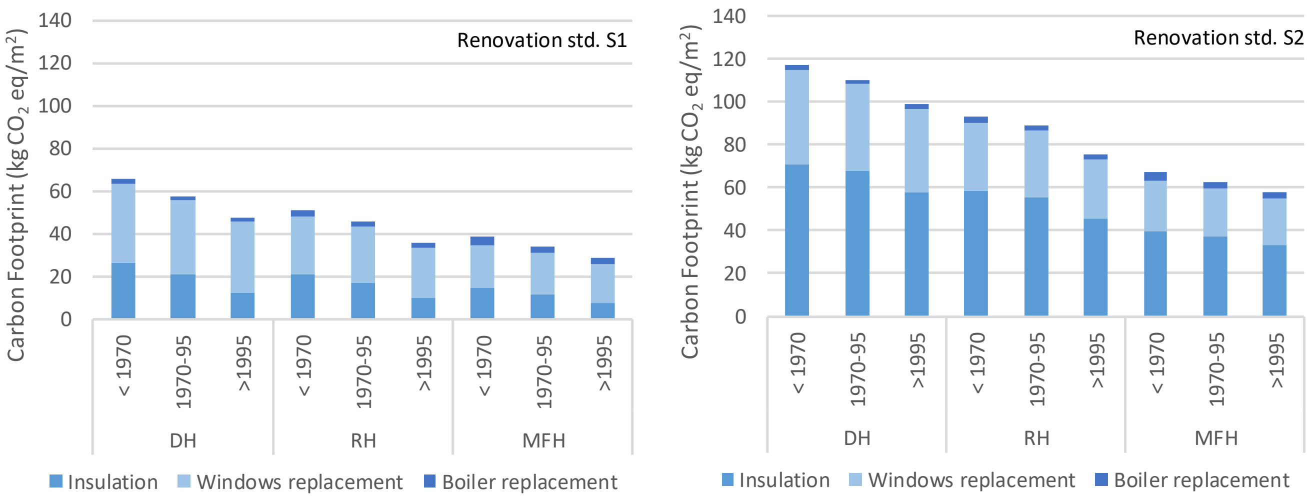

Figure 5 Average carbon footprint of renovation residential buildings in Esch-sur-Alzette per floor area unit per housing type (detached houses DH, row houses RH and multi-family houses MFH) and period of construction, implementing different renovation standards (S1 and S2).

Due to the prominence of building envelope measures, we assess the sensitivity of the renovation impacts to the insulating material and type of window frame, complying with the renovation standards S1 and S2 (Table 5). Changing type of insulation panels entails a variation in the order of 6-7% and 13-15% for renovation standard S1 and S2 respectively, depending on the impact of material production and insulation thickness needed to comply with the U-value requirements. The material with the lowest impact is rockwool, due to significantly lower production impacts, despite its higher conductivity compared to EPS and therefore higher thickness required. On the other hand, both XPS and glasswool result in higher impacts, due respectively to higher production impacts per unit and thicker panels required. The influence of the type of window framing is even higher, with variations of 16-51% (12-16%) on the impact for renovation according to standard S1 (S2). While wooden frames offer lower impact compared to PVC frames, metallic frames significantly increase the impact up to 51%, due to the use of fossil fuels in the metal production, which requires high temperatures. Overall, varying the type of insulation has the greatest effects for renovation standard S2, where greater insulation thickness is required, while the type of window has a higher influence in renovation standard S1.

Table 5 Sensitivity of insulation material and window type on the impact for the renovation stage (average across the housing stock). Reference are insulation in EPS and windows with wooden frame.

Renovation operation	Renovation standard			
(parameter varied)	Renovation Standard S1		Renovation Standard S2	
	Average impact for complete renovation	Difference with reference (%)	Average impact for complete renovation	Difference with reference (%)

	(kg CO_2 eq./m^2y)		(kg CO_2 eq./m^2y)	
Thermal insulation (insulating material)				
EPS (reference)	1.35	-	2.47	-
XPS	1.44	7%	2.83	15%
Glasswool	1.43	6%	2.79	13%
Rockwool	1.26	-7%	2.13	-14%
Windows replacement (frame material)				
PVC (reference)	1.60	-	2.96	-
Wood	1.35	-16%	2.47	-16%
Metal	2.43	51%	3.30	12%

4.2.3. Mapping mitigation potential at the city scale

The carbon footprint results can be visualised as geospatial layers in GIS and spatially analysed, to improve the localization of hotspots and support renovation strategies. Two mapped layers are reported here as an example, displaying the spatial distribution of impact intensity and total impact reduction potential across the city using fixed time horizons accounting for the carbon footprint. Values are located on the building responsible for the environmental impacts.

Figure 6 shows the spatial distribution of carbon footprint intensity reduction potential per unit of floor area by implementing renovation measures (standard S1). The impact reduction intensity is driven by housing type, vintage and state of renovation (cfr. section 4.2.1) and is rather evenly distributed in the central areas of the city (values from 20 to 40 kg CO_2 eq./m^2y), due to the prevalence of relatively old MFH and RH. Many areas in the suburbs are characterized by old SFH and RH (especially ancient mines workers neighbourhoods), therefore offering higher impact intensity reduction potential. In contrast, new developments in the Northern outskirt of the city offer the lowest impact intensity reduction potential.

A different pattern emerges in Figure 7, showing the spatial distribution of total reduction potential by implementing renovation measures (standard S1). For the total reduction potential, both the intensity reduction potential and the floor surface amount influence the results. The highest reduction potential is concentrated in the areas adjacent to the city centre, resulting from the combination of higher urban density, housing types (MFH and RH) and building vintage. Areas in the suburbs, even with relatively old buildings and high intensity reduction potential, have a lower total reduction potential due to a sprawling urban form and building types with lower total floor surface areas (DH and RH). At the city scale, the total potential for carbon footprint reduction is 51% by implementing renovation standard S1 and 66% by implementing renovation standard S2.

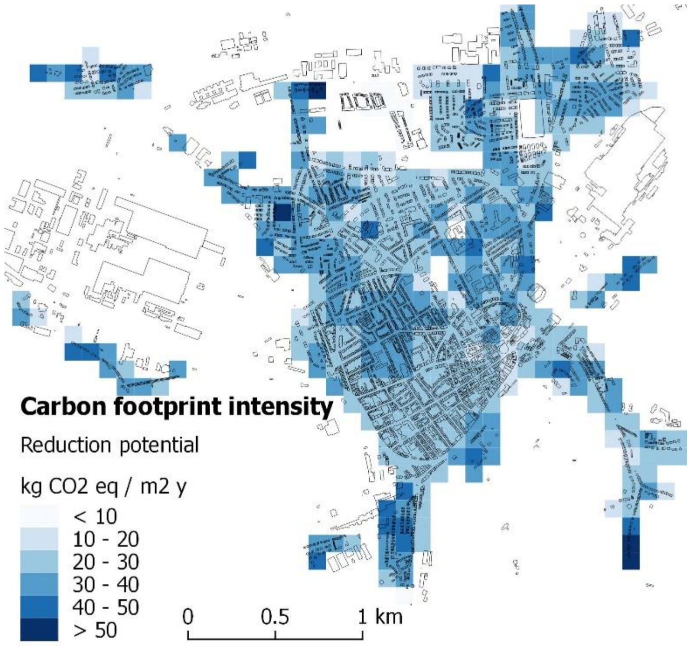

Figure 6 Spatial distribution of carbon footprint intensity reduction potential of residential buildings in Esch-sur-Alzette after implementing renovation measures (renovation standard S1) in kg CO_2 eq. per floor surface area per year.

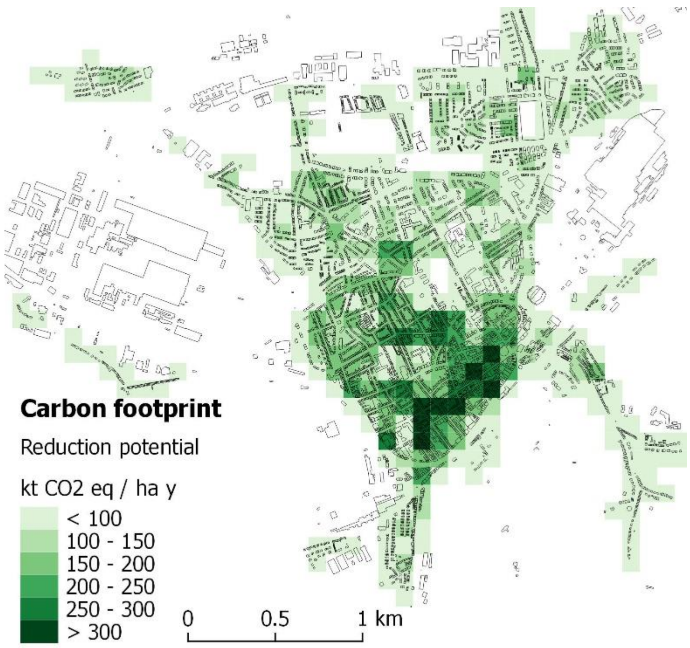

Figure 7 Spatial distribution of carbon footprint total reduction potential of residential buildings in Esch-sur-Alzette after implementing renovation measures (renovation standard S1) in kt CO_2 eq. per hectare per year.

4.2.4. Renovation scenarios

After estimating the theoretical impact reduction potential of renovation operations for the existing housing stock of Esch-sur-Alzette, we carried out a time-dependent evaluation of the different renovation scenarios over a period of 15 years (2015-2030). Figure 8 shows the variation over time in the carbon footprint of the entire housing stock combining different renovation rates (R1, R2) and renovation standards (S1, S2). Fixed time horizons (100 years) were used here for emissions accounting. At the current renovation rate of 0.5% (R1), only modest reductions of 3-4% in emissions associated with the buildings operation can be achieved by 2030 (Table 6). Increasing the renovation rate to 3.0% (R2), entails a much higher reduction up to 21% and 28%, respectively with renovation standard S1 and S2. These results reveal that accelerating renovation operations is vital in achieving significant reduction of the carbon footprint at the city level. Moreover, the effect of tightening the renovation standard on carbon footprint reduction is greater when combined with higher renovation rates.

The increase in carbon footprint for renovating buildings at a rate R1 amounts to 0.17-0.23 ktCO_2 eq./y respectively for S1 and S2 (Table 6). This amount increases considerably up to 1.14-1.61 ktCO_2 eq./y at a renovation rate R2, depending on the renovation standard (cfr. the coloured ribbons displayed in Figure 8), resulting in a non-negligible additional 17.15-24.13 ktCO_2 eq. emitted along the entire 15 years period. Overall, neglecting the impact of the renovation stage results in an overestimation of the benefits of renovation by an average 8-9% per year on a city scale.

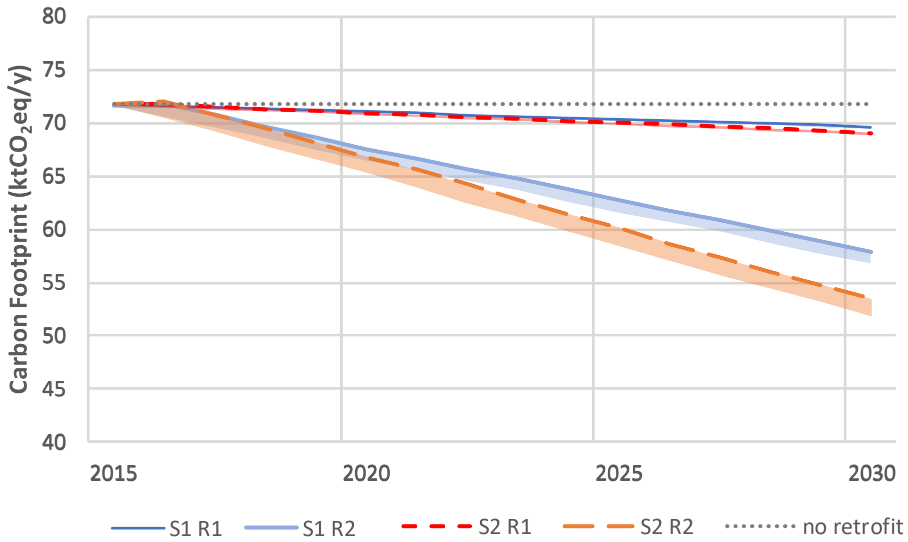

Figure 8. Carbon footprint of all existing residential buildings in Esch-sur-Alzette under four renovation scenarios combining two renovation standards (S1 and S2) and two renovation rates (R1 and R2). Emissions accounted with fixed time horizons (100 years). Lines indicate the total yearly carbon footprint, coloured areas the yearly embodied impact for renovation.

Table 6 Variations in the carbon footprint of existing residential buildings in Esch-sur-Alzette under four renovation scenarios combining two renovation standards (S1 and S2) and two renovation rates (R1 and R2). Emissions accounted with fixed time horizons (100 years).

Scenario	Carbon Footprint			
	Operation in 2030 ($ktCO_2$eq./y)	Reduction in operation by 2030 ($ktCO_2$eq/y)	Renovation – yearly average 2015-2030 ($ktCO_2$eq./y)	Renovation – total 2015-2030 ($ktCO_2$eq.)
No renovation	71.65	-	-	-
S1 R1	69.47	2.17 (3%)	0.17	2.49
S2 R2	68.74	2.91 (4%)	0.23	3.49
S1 R2	56.81	14.84 (21%)	1.14	17.15
S2 R2	51.68	19.96 (28%)	1.61	24.13

Having the operation and renovations interventions in the building stock explicitly modelled over time, enables a time-dependent accounting of emissions towards a fixed end-point (100 years in our analysis) by using time-adjusted CFs. We compared the results of total cumulative carbon emissions of the housing stock over the 15 years of the analysis (2015-2030) in the case of fixed and variable time horizons and found a difference of 5.3-5.5% between the two (see Supplementary Material, SM8). Figure 9 shows the cumulative reduction of total carbon footprint for different scenarios compared to a scenario with no renovation, using fixed and variable time horizons. The results demonstrate that, with a time-dependent emissions accounting, net carbon footprint reductions are lower, albeit by a small amount, compared to traditional accounting. This difference is expected to increase when considering longer periods for the scenarios. The net difference in carbon footprint cumulated over 15 years compared to the case of no renovations is minimal for the scenarios with renovation rate R1 (1.0-1.4%) and significantly higher with renovation rate R2, up to 9.3-9.6% with R2 and S2. Note that these values are lower than the ones showed in Table 6, as they refer to cumulative differences over 15 years of analysis rather than reductions achieved by the end of the same time period. In this case as well, the renovation operations counterbalance a non-negligible portion of the carbon footprint reductions in the operation of buildings.

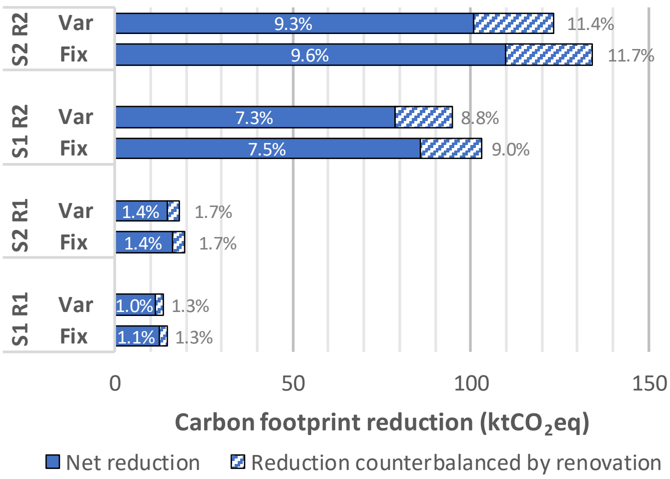

Figure 9. Cumulative reduction of total carbon footprint of existing residential buildings in Esch-sur-Alzette over 15 years (2015-2030) compared to a scenario with no renovation. Results are shown for four renovation scenarios combining two renovation standards (S1 and S2) and two renovation rates (R1 and R2), and for calculation of emissions with variable (Var) and fixed (Fix) time horizons and characterization factors. Both net reductions and reductions in operational stage counterbalanced by renovation operations are reported.

5. Discussion

We presented a bottom-up framework for the LCA of renovation scenarios in urban settlements. This study contributes to the advancement of urban building stock modelling along three dimensions: 1) proposing LCA in order to have a holistic estimation of environmental impacts and to avoid overestimation of the renovation benefits expressed in operational energy terms; 2) integrating a detailed building-by-building model based on detailed geospatial analysis using GIS to obtain an improved characterization of the building stock and a spatial characterization of the results; 3) considering the time dimension both in the life cycle inventory (renovation scenarios) and life cycle impact assessment (time-adjusted global warming potential) phases. To the best of our knowledge, this is one of the first studies addressing urban renovation scenarios along both spatial and temporal dimensions, and proposing a time-dependent approach for the impact assessment. This framework can support local authorities and urban planners in developing pathways and priority strategies for energy and environmental impact mitigations. The methods are scalable and easily transferable to other contexts, provided that a minimum dataset is available (see Supplementary Material, SM2).

The following sections discuss the implications of using a lifecycle approach for urban building renovation scenarios, spatially and temporally explicit assessment, limitations and future developments.

5.1. *Towards a lifecycle approach for urban building renovation*

Current urban building stock models largely focus on operational energy savings due to renovation. Our results demonstrate the importance of considering the impacts of the renovation stage, especially when moving towards low-energy and passive solutions. Neglecting those impacts leads to an overestimation of environmental benefits. In the case of the housing stock in Esch-sur-Alzette these resulted in an average of 8-9% for the carbon footprint, but are expected to be higher for accelerated and more aggressive renovation scenarios. The impacts in the renovation stage account for up to 11-16% of the residual lifecycle impacts of residential buildings when implementing advanced renovation solution (standard S2). Moreover, they strongly depend on the materials chosen for renovation and target renovation standard, with potential variations in the range of 6-15% for thermal insulation and 12-51% for windows replacement. These results gain even more relevance in the light of the envisaged shift towards zero-energy buildings solutions, for which stages other than operation will dominate the lifecycle impacts. Urban carbon mitigation policies for buildings should therefore consider the impact associated with the renovation stage and encourage the use of low embodied-carbon materials, beyond the reduction of operational energy, especially for advanced renovation operations.

5.2. *Spatial assessment*

Our framework for the assessment of urban building renovation integrates GIS and geospatial analysis, energy modelling and carbon footprinting, allowing for explicit spatial (location based) assessment. The integration with GIS allows gathering building data in a systematic and effective way, improving the data availability and accuracy for building geometry and characteristics, otherwise scarcely available at this scale. In particular, a systematic estimation of the surface areas of outer building envelopes is possible using the developed GIS processing procedure, allowing for quantitative assessment of the material amounts required for renovation, such as building insulation and window replacement. This spatial dataset also feeds the energy model, allowing for explicit accounting of building geometry and characteristics in the calculation of energy demand and savings.

While gaps still exist in data on building characteristics, materials and current refurbishment state at the urban scale, this framework is flexible in incorporating new data at the building level once they become available (e.g. from energy passport registers, or refurbishment records). In case of missing data, a probabilistic approach can be used to distribute building characteristics across the stock based on statistics and building libraries. This advances the common archetype approach, where only one set of building characteristics is attributed to specific building categories, often disregarding past refurbishment operations, which could significantly influence the energy performance. Spatial constraints can be explicitly accounted for, as we demonstrated for refurbishment restrictions for old buildings in the historical city centre, and presence of district heating network.

The integration with GIS further supports the presentation of results as spatial maps, the identification of hotspots, and the improvement of communication with stakeholders. The maps of carbon reduction potential can be used to identify neighbourhoods suitable for implementation of larger renovation plans and to orient renovation programs. Results are scalable to different levels, such as building, neighbourhood and city, depending on the desired target level.

5.3. Temporal assessment

This framework allows for explicit accounting of the temporal evolution of the building stock, essential to develop building renovation scenarios. While the roll out of building renovation operations was considered in a simplified way, with fixed renovation rates, the model enables assessing the combined effect of advancing renovation standards and accelerating building renovation. The results for the city of Esch-sur-Alzette demonstrated that accelerating the renovation rate from the current rate of 0.5% (R1) to 3.0% (R2) has a stronger effect on the total impact reduction than solely tightening the renovation standard from current (S1) to advanced (S2). The influence of improved renovation standard is higher when considering the accelerated renovation rate R2, resulting in potential impact reductions for the operation of 28% by 2030. These results highlight the importance of simultaneously speeding up and advancing renovation standard for effective carbon mitigation strategies.

A temporally explicit inventory allows the use of time-adjusted carbon footprint accounting. This has the advantage of avoiding distortions from assuming the same time horizon for all emissions, regardless of when they occur with respect to the end point of the analysis. Our results demonstrated that using time-adjusted emissions has implications on the relative weight of the impacts related to the operational and renovation stages, being the former lowered due to a long extension in time. In renovation scenarios, the use of time-adjusted emission calculation results in lower benefits regarding the reduction of emissions in the operational stage. This could introduce bias in the results if not properly considered, especially for medium to long-term scenarios.

5.4. Limitations and future developments

The development of an urban building stock carbon footprint framework is challenging due to the complexity of the modelled system and inevitably leads to some limitations, that will be addressed in future developments.

One of the main limitations consists in data availability on buildings at the urban scale, in particular for building materials, refurbishment state, usage of buildings and service life. Despite the use of accurate GIS data, the model depends on assumptions based on statistical data, national standards, regulations and previous studies. These limitations were partly overcome by using a stochastic approach when data were available at a higher aggregation level.

This study focused on the existing building stock and renovation only. Demolitions and new buildings construction should be included for a more comprehensive assessment of mitigation scenarios. The estimation of energy savings and carbon mitigation driven by renovation should be considered as theoretical, as renovation rates for different building categories might change in the future and cost-effectiveness aspects were not considered.

For the energy demand analysis, we used a model in semi-steady state, according to current building regulations and in line with previous similar studies limited to space heating in residential buildings [91]. Dynamic energy models come with more accurate energy estimates, in particular for space cooling and non-residential buildings, at the cost of higher computation burdens. Integration of dynamic models within an LCA framework for building stock renovation will be the object of future research.

Some caveats also exist in the LCI data and boundaries. The residual service life of buildings was fixed at 30 years for the calculation of impact reduction potential of renovation, in accordance with other studies [89]. In reality, the residual service life could greatly vary depending on a number of factors, including the state of conservation of buildings and cost-effectiveness of demolition versus refurbishment/renovation.

The LCI was limited to operation and renovation stage, while other stages were excluded. The end-of-life stage was assessed in a previous study [54] and a joint assessment of end-of-life versus renovation strategies should be addressed by further research. In the renovation stage, we included material production and transportation to the building site. Implementation of refurbishment operations on site and waste management were neglected, as expected to entail minor impacts.

Results validation was carried out by comparing energy demand results against measured results at post-code level, showing reasonable agreement (see Supplementary Material, SM7). Results might be less accurate at the individual building level, due to higher uncertainty in the building characteristics and use.

Future developments will include a comprehensive uncertainty and sensitivity analysis to identify key parameters influencing the results. We envisage to apply this framework to other cities in different countries and extend the assessment to non-residential buildings. A broader range of environmental indicators may be used for a more comprehensive assessment of the implication of building renovation on the environment.

Finally, we need to point out that the time-adjusted assessment carried out in this study (i.e. the time differentiation in the CFs for GWP in the impact assessment phase) is not a full dynamic LCA, in the sense that time differentiation in the background inventory is missing. Comprehensively including temporality in LCA means being able to consider the effect of the temporal variations of: building occupancy; thermal resistance of insulation materials and efficiency of other building components; production capacity of energy production equipment (such as building-integrated photovoltaic panels); energy mix scenarios; biogenic carbon emissions (especially for buildings with significant amount of wood); end of life technologies and infrastructures [92]. A tool for dynamic LCA calculation able to take into account temporality in the LCI, in the background and the foreground system, was recently proposed in [62,93–95]. Its application to the case of building renovation is planned in a future study.

6. Conclusion

We developed a spatially explicit LCA framework to evaluate the environmental impact of urban building stocks and renovation scenarios using a building-by-building approach. The methodology was tested for the existing housing stock of Esch-sur-Alzette, limited to carbon footprint assessment, and renovation scenarios were developed considering several renovation rates and standards.

Results for Esch-sur-Alzette show that the renovation stage represents 4-5% to 11-16% of the carbon footprint in the residual service life of existing buildings, respectively after a conventional or advanced renovation. Under current renovation rates, the carbon footprint reduction expected by 2030 will be limited to 3-4%. Accelerating renovation interventions enables carbon reductions up to 28% by 2030 when combined with advanced renovation standards. Carbon reductions in the operational stage of buildings are offset by 8-9% due to the impacts of renovation. Using time-adjusted emissions results in higher weight for the renovation stage and slightly lower benefits for renovation.

This study advanced the current state of the art by integrating carbon footprint, energy modelling, GIS and scenario developments to provide spatially and temporally explicit assessment of building renovation at the city scale. The developed framework can be used to explore renovation strategies and support decisions for building stock renovation.

Future research work to continue this study could focus on introducing additional temporality in every phase of the LCA of buildings. As recently highlighted [96], temporal details in socio-economic parameters, like technological progress and occupant behaviour could be targeted. For the former, some approaches based on computable equilibrium models have been proposed to include future trends of energy structure development [97,98]. For the latter, next to classical approaches such as regression analysis, mathematical simulation and environmental simulation, new approaches based on agent-based simulations [99] could be investigated.

Acknowledgements

This study has been funded by the postdoctoral research project “DAEDALUS”, supported by the National Research Fund, Luxembourg (FNR) [Grant agreements AFR-7579115] and the Luxembourg Institute of Science and Technology. Declarations of interest: none.

The City Council of Esch-sur-Alzette is kindly acknowledged for collaborating to this project with relevant discussion and data provision. We would like to thank Mr. Christian Braun, Dr. Alexandre Bertrand and Dr. Luís De Sousa for the valuable support and discussion.

References

[1] Tukker AE Al. Environmental Impact of Products (EIPRO) 2006;22284:1–13. https://doi.org/ISBN-10: European Communities 2006.

[2] European Parliament. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the

energy performance of buildings (recast). Off J Eur Union 2010:13–35. https://doi.org/doi:10.3000/17252555.L_2010.153.eng.

[3] Vilches A, Garcia-martinez A, Sanchez-monta B. Life cycle assessment (LCA) of building refurbishment : A literature review 2017;135:286–301. https://doi.org/10.1016/j.enbuild.2016.11.042.

[4] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency. n.d.

[5] Ma Z, Cooper P, Daly D, Ledo L. Existing building retrofits: Methodology and state-of-the-art. Energy Build 2012;55:889–902. https://doi.org/10.1016/j.enbuild.2012.08.018.

[6] United Nations. World Urbanization Prospects: The 2011 Revision. New York: United Nations; 2012. https://doi.org/10.2307/2808041.

[7] Swan LG, Ugursal VI. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. Renew Sustain Energy Rev 2009;13:1819–35. https://doi.org/10.1016/j.rser.2008.09.033.

[8] Kavgic M, Mavrogianni A, Mumovic D, Summerfeld A, Stevanovic Z, Djurovic-Petrovic M. A review of bottom-up building stock models for energy consumption in the residential sector. Build Environ 2010;45:1683–97.

[9] Reinhart CF, Cerezo Davila C. Urban building energy modeling - A review of a nascent field. Build Environ 2016;97:196–202. https://doi.org/10.1016/j.buildenv.2015.12.001.

[10] Abbasabadi N, Mehdi Ashayeri JK. Urban energy use modeling methods and tools: A review and an outlook. Build Environ 2019;161:106270. https://doi.org/10.1016/j.buildenv.2019.106270.

[11] Brøgger M, Wittchen KB. Estimating the energy-saving potential in national building stocks – A methodology review. Renew Sustain Energy Rev 2018;82:1489–96. https://doi.org/10.1016/j.rser.2017.05.239.

[12] Frayssinet L, Merlier L, Kuznik F, Hubert J, Milliez M. Modeling the heating and cooling energy demand of urban buildings at city scale. Renew Sustain Energy Rev 2018;81:2318–27. https://doi.org/10.1016/j.rser.2017.06.040.

[13] Li W, Zhou Y, Cetin K, Eom J, Wang Y, Chen G. Modeling urban building energy use : A review of modeling approaches and procedures. Energy 2017;141:2445–57. https://doi.org/10.1016/j.energy.2017.11.071.

[14] Cabeza LF, Rincón L, Vilariño V, Pérez G, Castell A. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renew Sustain Energy Rev 2014;29:394–416. https://doi.org/10.1016/j.rser.2013.08.037.

[15] Heeren N, Jakob M, Martius G, Gross N, Wallbaum H. A component based bottom-up building stock model for

comprehensive environmental impact assessment and target control. Renew Sustain Energy Rev 2013;20:45–56. https://doi.org/10.1016/j.rser.2012.11.064.

[16] Wang Q, Laurenti R, Holmberg S. A novel hybrid methodology to evaluate sustainable retrofitting in existing Swedish residential buildings. Sustain Cities Soc 2015;16:24–38. https://doi.org/10.1016/j.scs.2015.02.002.

[17] Mastrucci A, Marvuglia A, Leopold U, Benetto E. Life Cycle Assessment of building stocks from urban to transnational scales: A review. Renew Sustain Energy Rev 2017;74:316–32. https://doi.org/10.1016/j.rser.2017.02.060.

[18] Albertí J, Balaguera A, Brodhag C, Fullana-i-palmer P. Towards life cycle sustainability assessment of cities . A review of background knowledge. Sci Total Environ 2017;609:1049–63. https://doi.org/10.1016/j.scitotenv.2017.07.179.

[19] Albertí J, Roca M, Brodhag C, Fullana-i-palmer P. Allocation and system boundary in life cycle assessments of cities. Habitat Int 2018:0–1. https://doi.org/10.1016/j.habitatint.2018.11.003.

[20] Albertí J, Brodhag C, Fullana-i-palmer P. First steps in life cycle assessments of cities with a sustainability perspective : A proposal for goal , function , functional unit , and reference fl ow. Sci Total Environ 2019;646:1516–27. https://doi.org/10.1016/j.scitotenv.2018.07.377.

[21] Chau CK, Leung TM, Ng WY. A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. Appl Energy 2015;143:395–413. https://doi.org/10.1016/j.apenergy.2015.01.023.

[22] Buyle M, Braet J, Audenaert A. Life cycle assessment in the construction sector: A review. Renew Sustain Energy Rev 2013;26:379–88. https://doi.org/10.1016/j.rser.2013.05.001.

[23] Ortiz O, Castells F, Sonnemann G. Sustainability in the construction industry: A review of recent developments based on LCA. Constr Build Mater 2009;23:28–39. https://doi.org/10.1016/j.conbuildmat.2007.11.012.

[24] Anand CK, Amor B. Recent developments, future challenges and new research directions in LCA of buildings: A critical review. Renew Sustain Energy Rev 2017;67:408–16. https://doi.org/10.1016/j.rser.2016.09.058.

[25] Lotteau M, Loubet P, Pousse M, Dufrasnes E, Sonnemann G. Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale. Build Environ 2015;93:165–78. https://doi.org/10.1016/j.buildenv.2015.06.029.

[26] Allacker K, Castellani V, Baldinelli G, Bianchi F, Baldassarri C, Sala S. Energy simulation and LCA for macro-scale analysis of eco-innovations in the housing stock 2018.

[27] Kendall A. Time-adjusted global warming potentials for LCA and carbon footprints. Int J Life Cycle Assess 2012;17:1042–9. https://doi.org/10.1007/s11367-012-0436-5.

[28] Levasseur A, Cavalett O, Fuglestvedt JS, Gasser T, Johansson DJA, Jørgensen S V, et al. Enhancing life cycle impact assessment from climate science : Review of recent findings and recommendations for application to LCA. Ecol Indic 2016;71:163–74. https://doi.org/10.1016/j.ecolind.2016.06.049.

[29] Anderson JE, Wulfhorst G, Lang W. Expanding the use of life-cycle assessment to capture induced impacts in the built environment. Build Environ 2015;94:403–16. https://doi.org/10.1016/j.buildenv.2015.08.008.

[30] Nichols B, Kockelman K. Urban Form and Life-Cycle Energy Consumption: Case Studies for Five Us Cities. CeUtexasEdu 2011:1–16.

[31] Norman J, Norman J, MacLean HL, MacLean HL, Kennedy C a., Kennedy C a. Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions. J Urban Plan Dev 2006;132:10. https://doi.org/10.1061/(ASCE)0733-9488(2006)132:1(10).

[32] Saner D, Heeren N, Jäggi B, Waraich R a., Hellweg S. Housing and Mobility Demands of Individual Households and their Life Cycle Assessment. Environ Sci Technol 2013;47:5988–97. https://doi.org/10.1021/es304084p.

[33] Saner D, Vadenbo C, Steubing B, Hellweg S. Regionalized LCA-based optimization of building energy supply: Method and case study for a swiss municipality. Environ Sci Technol 2014;48:7651–9. https://doi.org/10.1021/es500151q.

[34] Moffatt S. Stock Aggregation. Methods for Evaluating the Environmental Performance of Building Stocks. 2004.

[35] Österbring M, Mata É, Thuvander L, Mangold M, Johnsson F, Wallbaum H. A differentiated description of building-stocks for a georeferenced urban bottom-up building-stock model. Energy Build 2016;120:78–84. https://doi.org/10.1016/j.enbuild.2016.03.060.

[36] García-Pérez S, Sierra-Pérez J, Boschmonart-Rives J. Environmental assessment at the urban level combining LCA-GIS methodologies: A case study of energy retrofits in the Barcelona metropolitan area. Build Environ 2018;134:191–204. https://doi.org/10.1016/j.buildenv.2018.01.041.

[37] Stephan A, Athanassiadis A. Towards a more circular construction sector : Estimating and spatialising current and future non-structural material replacement fl ows to maintain urban building stocks. Resour Conserv Recycl 2018;129:248–62. https://doi.org/10.1016/j.resconrec.2017.09.022.

[38] Pauliuk S, Sjöstrand K, Müller DB. Transforming the Norwegian Dwelling Stock to Reach the 2 Degrees Celsius Climate Target. J Ind Ecol 2013;17:542–54. https://doi.org/10.1111/j.1530-9290.2012.00571.x.

[39] Vásquez F, Løvik AN, Sandberg NH, Müller DB. Dynamic type-cohort-time approach for the analysis of energy reductions strategies in the building stock. Energy Build 2020;111:37–55. https://doi.org/10.1016/j.enbuild.2015.11.018.

[40] Augiseau V, Candidate PD, Barles S. Studying construction materials flows and stock : A review. Resour Conserv Recycl 2017;123:153–64. https://doi.org/10.1016/j.resconrec.2016.09.002.

[41] Nichols BGB, Kockelman KK. Urban Form and Life-Cycle Energy Consumption: Case Studies for Five Us Cities. CeUtexasEdu 2011;8:1–16. https://doi.org/10.5198/jtlu.2015.598.

[42] Baldassarri C, Allacker K, Reale F, Castellani V. Consumer Footprint. Basket of Products indicator on Housing. EUR 28765 EN, Publications Office of the European Union, Luxembourg; 2017. https://doi.org/10.2760/05316.

[43] Onat NC, Egilmez G, Tatari O. Towards greening the U.S. residential building stock: A system dynamics approach. Build Environ 2014;78:68–80. https://doi.org/10.1016/j.buildenv.2014.03.030.

[44] Building Performance Institute Europe (BPIE). Europe's Buildings Under The Microscope. 2011.

[45] Reyna JL, Chester M V. The Growth of Urban Building Stock: Unintended Lock-in and Embedded Environmental Effects. J Ind Ecol 2014;19:524–37. https://doi.org/10.1111/jiec.12211.

[46] Sandberg NH, Sartori I, Vestrum MI, Brattebø H. Explaining the historical energy use in dwelling stocks with a segmented dynamic model : Case study of Norway 1960 – 2015. Energy Build 2016;132:141–53. https://doi.org/10.1016/j.enbuild.2016.05.099.

[47] Augiseau V, Candidate PD, Barles S, Baldassarri C, Allacker K, Reale F, et al. Stock dynamics for forecasting material flows — Case study for housing in The Netherlands. Energy Build 2017;132:153–64. https://doi.org/10.2760/05316.

[48] Sandberg NH, Sartori I, Heidrich O, Dawson R, Dascalaki E, Dimitriou S, et al. Dynamic building stock modelling: Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU. Energy Build 2016;132:26–38. https://doi.org/10.1016/j.enbuild.2016.05.100.

[49] Exner D, Alonzo VDD, Paoletti G, Pascual R, Pernetti R. Building-Stock Analysis for the Definition of an Energy Renovation Scenario on the Urban Scale. Smart Sustain. Plan. Cities Reg., Springer International Publishing Switzerland; 2017, p. 33–54. https://doi.org/10.1007/978-3-319-44899-2.

[50] Levasseur A, Cavalett O, Fuglestvedt JS, Gasser T, Johansson DJA, Jørgensen S V, et al. Enhancing life cycle impact assessment from climate science : Review of recent findings and recommendations for application to LCA. Ecol Indic 2016;71:163–74. https://doi.org/10.1016/j.ecolind.2016.06.049.

[51] Rodrigues F, Carvalho MT, Evangelista L, De Brito J. Physical-chemical and mineralogical characterization of fine aggregates from construction and demolition waste recycling plants. J Clean Prod 2013;52:438–45. https://doi.org/10.1016/j.jclepro.2013.02.023.

[52] Jørgensen S V, Hauschild MZ. Need for relevant timescales when crediting temporary carbon storage. Int J Life Cycle Assess 2013;18:747–54. https://doi.org/10.1007/s11367-012-0527-3.

[53] Tooke TR, van der Laan M, Coops NC. Mapping demand for residential building thermal energy services using airborne LiDAR. Appl Energy 2014;127:125–34. https://doi.org/http://dx.doi.org/10.1016/j.apenergy.2014.03.035.

[54] Mastrucci A, Marvuglia A, Popovici E, Leopold U, Benetto E. Geospatial characterization of building material stocks for the life cycle assessment of end-of-life scenarios at the urban scale. Resour Conserv Recycl 2017. https://doi.org/10.1016/j.resconrec.2016.07.003.

[55] Alhamwi A, Medjroubi W, Vogt T, Agert C. GIS-based urban energy systems models and tools: Introducing a model for the optimisation of flexibilisation technologies in urban areas. Appl Energy 2017;191:1–9. https://doi.org/10.1016/j.apenergy.2017.01.048.

[56] Eicker U, Zirak M, Bartke N, Romero Rodríguez L, Coors V. New 3D model based urban energy simulation for climate protection concepts. Energy Build 2018;163:79–91. https://doi.org/https://doi.org/10.1016/j.enbuild.2017.12.019.

[57] Buffat R, Froemelt A, Heeren N, Raubal M, Hellweg S. Big data GIS analysis for novel approaches in building stock modelling. Appl Energy 2017;208:277–90. https://doi.org/https://doi.org/10.1016/j.apenergy.2017.10.041.

[58] Jakob M, Wallbaum H, Catenazzi G, Martius G, Nägeli C, Sunarjo B. Spatial Building Stock Modelling To Assess Energy- Efficiency and Renewable Energy in an Urban Context. Cisbat 2013 2013:1047–52.

[59] Sandberg HN, Sartori I, Vestrum MI, Brattebø H, Sandberg NH, Sartori I, et al. Using a segmented dynamic dwelling stock model for scenario analysis of future energy demand : The dwelling stock of Norway 2016 – 2050. Energy Build 2017;146:220–32. https://doi.org/10.1016/j.enbuild.2017.04.016.

[60] Buffat R, Schmid L, Heeren N, Froemelt A, Raubal M, Hellweg S. GIS-based Decision Support System for Building Retrofit. Energy Procedia 2017;122:403–8. https://doi.org/10.1016/j.egypro.2017.07.433.

[61] Di Virgilio N. LCA-GIS Integrated Approach For A Sustainable Land Use Under Energy Crops. University of Bologna (Italy), 2012.

[62] Tiruta-barna L, Pigné Y, Navarrete Gutiérrez T, Benetto E. Framework and computational tool for the consideration of time dependency in Life Cycle Inventory: proof of concept. J Clean Prod 2016;116:198–206. https://doi.org/10.1016/j.jclepro.2015.12.049.

[63] Pigné Y, Gutiérrez TN, Gibon T, Schaubroeck T, Popovici E, Shimako AH, et al. A tool to operationalize dynamic LCA, including time differentiation on the complete background database. Int J Life Cycle Assess 2020;25:267–79.

https://doi.org/10.1007/s11367-019-01696-6.

[64] Bizjak M, Žalik B, Štumberger G, Lukač N. Estimation and optimisation of buildings' thermal load using LiDAR data. Build Environ 2018;128:12–21. https://doi.org/10.1016/J.BUILDENV.2017.11.016.

[65] Sandberg NH, Sartori I, Brattebø H. Sensitivity analysis in long-term dynamic building stock modeling - Exploring the importance of uncertainty of input parameters in Norwegian segmented dwelling stock model. Energy Build 2014;85:136–44. https://doi.org/10.1016/j.enbuild.2014.09.028.

[66] R Core Team. R: A language and environment for statistical computing. 2016.

[67] Postgresql T, Development G. PostgreSQL 9.4.0 Documentation 2016.

[68] PostGIS 2.0 Manual – SVN Revision (14621) (consulted: January 2018) 2016.

[69] QGIS Development Team. QGIS Geographic Information System 2009.

[70] GRASS Development Team. Geographic Resources Analysis Support System (GRASS) Software; Version 6.4; Open Source Geospatial Foundation Project; 2012 2012.

[71] Le Gouvernement du Grand-Duché de Luxembourg. Draft Integrated National Energy and Climate Plan. 2019.

[72] Le Gouvernement du Grand-Duché de Luxembourg. Fourth National Energy Efficiency Action Plan Luxembourg. 2017.

[73] Le Gouvernement du Grand-Duché de Luxembourg. Enhanced Building Renovation Strategy Additional strategies and measures. 2017.

[74] STATEC. Statistic Portal Grand Duchy of Luxembourg (consulted: January 2019) n.d.

[75] Le Gouvernement du Grand-Duché de Luxembourg. Second National Energy Efficiency Action Plan 2011.

[76] Mastrucci A, Pérez-López P, Benetto E, Leopold U, Blanc I. Global sensitivity analysis as a support for the generation of simplified building stock energy models. Energy Build 2017;149. https://doi.org/10.1016/j.enbuild.2017.05.022.

[77] DIN. DIN 4108-4 - Wärmeschutz und Energie-Einsparung in Gebäuden - Teil 4: Wärme- und feuchteschutztechnische Bemessungswerte. Wärmeschutz Und Energie-Einsparung Gebäuden- … 2007.

[78] Ministère de l'Economie et du commerce extérieur L. Leitfaden zur Verwendung von U-Wert-Typologien im Rahmen der Energie-passerstellung für bestehende Gebäude, v. 1.1. 2007.

[79] Règlement grand-ducal du 26 mai 2014. Performance énergétique des bâtiments d'habitation et fonctionnels. Meml - J Off Du Gd Du Luxemb A – N° 99 2014;99.

[80] Règlement grand-ducal du 23 juillet 2016 modifiant 1. le règlement grand-ducal modifié du 30 novembre 2007 concernant la performance énergétique des bâtiments d'habitation; 2. le règlement grand-ducal modifié du 31 août 2010 concernant la performance éner. Meml - J Off Du Gd Du Luxemb A – N° 146 2016:2463–511.

[81] Règlement grand-ducal du 12 décembre 2012 instituant un régime d'aides pour la promotion de l'utilisation rationnelle de l'énergie et la mise en valeur des énergies renouvelables dans le domaine du logement. 2012:3469–84.

[82] Iribarren D, Marvuglia A, Hild P, Guiton M, Popovici E, Benetto E. Life cycle assessment and data envelopment analysis approach for the selection of building components according to their environmental impact efficiency: A case study for external walls. J Clean Prod 2015;87:707–16. https://doi.org/10.1016/j.jclepro.2014.10.073.

[83] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 2016;21:1218–30. https://doi.org/10.1007/s11367-016-1087-8.

[84] Merzkirch A, Hoos T, Maas S, Scholzen F, Waldmann D. Wie genau sind unsere Energiepässe?: Vergleich zwischen berechneter und gemessener Endenergie in 230 Wohngebäuden in Luxemburg Wie genau sind unsere Energiepässe? Bauphysik 2014;36:40–3. https://doi.org/10.1002/bapi.201410007.

[85] STATEC. Regard 06 sur le stock des bâtiments et logements. 2015.

[86] Sartori I, Holck N, Brattebø H. Dynamic building stock modelling : General algorithm and exemplification for Norway. Energy Build 2016;132:13–25. https://doi.org/10.1016/j.enbuild.2016.05.098.

[87] CEN. EN 15643-2: 2011 Sustainability of construction works - Assessment of buildings - Part 2: Framework for the assessment of environmental performance 2011.

[88] CEN. EN 15978:2011 Sustainability of Construction Works – Assessment of Environmental Performance of Buildings – Calculation Method 2011.

[89] Nemry F, Uihlein A, Colodel CM, Wittstock B, Braune A, Wetzel C, et al. Environmental Improvement Potentials of Residential Buildings (IMPRO-Building). 2008. https://doi.org/10.2791/38942.

[90] Moschetti R, Mazzarella L, Nord N. An overall methodology to define reference values for building sustainability parameters. Energy Build 2015;88:413–27. https://doi.org/10.1016/j.enbuild.2014.11.071.

[91] Nouvel R, Mastrucci A, Leopold U, Baume O, Coors V, Eicker U. Combining GIS-based statistical and engineering urban heat consumption models: Towards a new framework for multi-scale policy support. Energy Build 2015;107. https://doi.org/10.1016/j.enbuild.2015.08.021.

[92] Negishi K, Tiruta-Barna L, Schiopu N, Lebert A, Chevalier J. An operational methodology for applying dynamic Life Cycle Assessment to buildings. Build Environ 2018;144:611–21. https://doi.org/https://doi.org/10.1016/j.buildenv.2018.09.005.

[93] Shimako AH, Tiruta-Barna L, Ahmadi A. Operational integration of time dependent toxicity impact category in dynamic LCA. Sci Total Environ 2017;599–600:806–19. https://doi.org/10.1016/J.SCITOTENV.2017.04.211.

[94] Shimako AH, Tiruta-Barna L, Bisinella de Faria AB, Ahmadi A, Spérandio M. Sensitivity analysis of temporal parameters in a dynamic LCA framework. Sci Total Environ 2018;624:1250–62. https://doi.org/https://doi.org/10.1016/j.scitotenv.2017.12.220.

[95] Shimako AH, Tiruta-Barna L, Pigné Y, Benetto E, Navarrete Gutiérrez T, Guiraud P, et al. Environmental assessment of bioenergy production from microalgae based systems. J Clean Prod 2016;139:51–60. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.08.003.

[96] Su S, Li X, Zhu Y, Lin B. Dynamic LCA framework for environmental impact assessment of buildings. Energy Build 2017;149:310–20. https://doi.org/10.1016/j.enbuild.2017.05.042.

[97] Matsumoto K. Energy Structure and Energy Security under Climate Mitigation Scenarios in China. PLoS One 2015;10:e0144884.

[98] Wang Z, Zhu Y, Zhu Y, Shi Y. Energy structure change and carbon emission trends in China. Energy 2016;115:369–77. https://doi.org/https://doi.org/10.1016/j.energy.2016.08.066.

[99] Micolier A, Taillandier F, Taillandier P, Bos F. Li-BIM, an agent-based approach to simulate occupant-building interaction from the Building-Information Modelling. Eng Appl Artif Intell 2019;82:44–59. https://doi.org/https://doi.org/10.1016/j.engappai.2019.03.008.