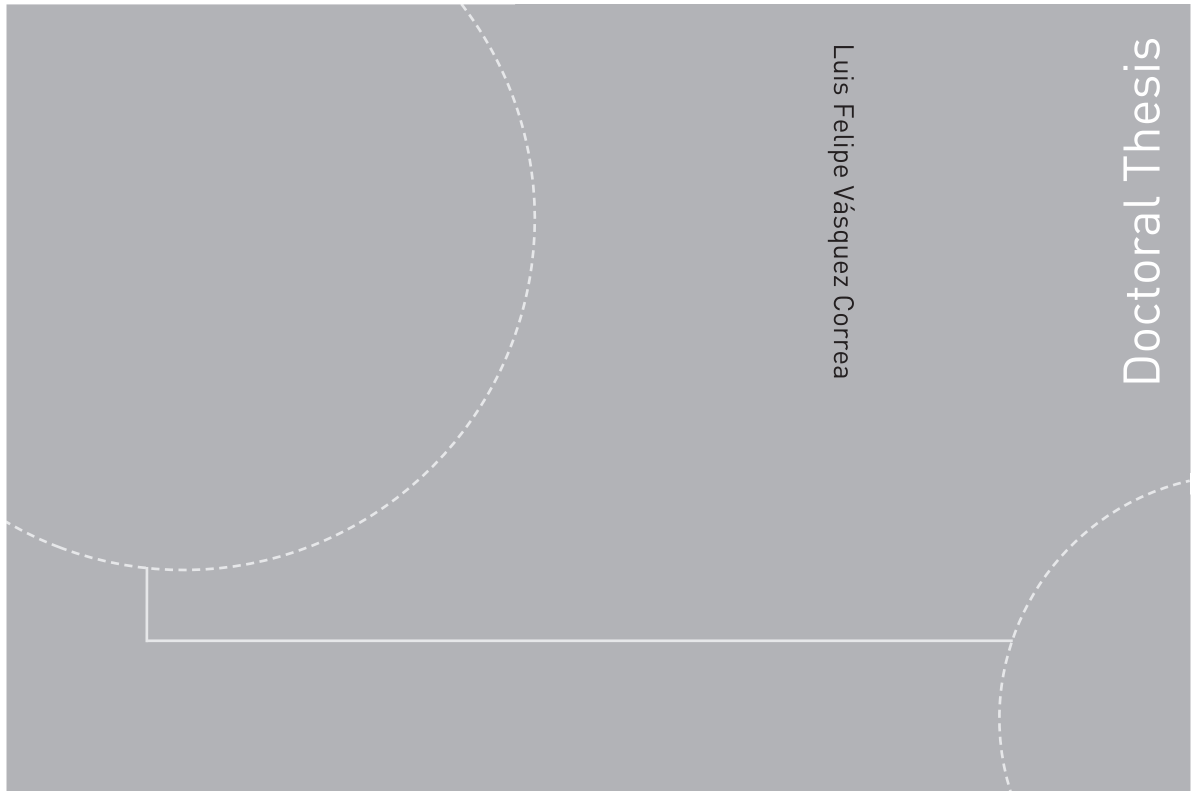
ISBN 978-82-326-3256-5 (printed version)
ISBN 978-82-326-3257-2 (electronic version)
ISSN 1503-8181



NTNU
Norwegian University of
Science and Technology

Luis Felipe Vásquez Correa

Doctoral theses at NTNU, 2018:233

NTNU

Doctoral Thesis

NTNU
Norwegian University of
Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Doctoral theses at NTNU, 2018:233

Luis Felipe Vásquez Correa

Demographically-Extended Socioeconomic Metabolism

A step towards addressing human needs and wants in resources' modelling

NTNU
Norwegian University of
Science and Technology

Luis Felipe Vásquez Correa

Demographically-Extended Socioeconomic Metabolism

A step towards addressing human needs and wants in resources' modelling

Thesis for the degree of Philosophiae Doctor

Trondheim, July 2018

Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

NTNU
Norwegian University of
Science and Technology

NTNU
Norwegian University of Science and Technology

Thesis for the degree of Philosophiae Doctor

Faculty of Engineering
Department of Energy and Process Engineering

ISBN 978-82-326-3256-5 (printed version)
ISBN 978-82-326-3257-2 (electronic version)
ISSN 1503-8181

Doctoral theses at NTNU, 2018:233

MILJØMERKET 241 TRYKKSAK 731

Printed by Skipnes Kommunikasjon as

"It is in the shelter of each other that we live in"

Irish Proverb

Abstract

Sustainable sociometabolic patterns are required to overcome unsatisfied needs, inequalities, and environmental problems, especially because of the expected population growth and rising living standards. To inform socioeconomic patterns that promote a resource and impact decoupled human development and well-being, it is imperative to have a comprehensive understanding of the human population, the built environment, the natural environment, and their linkages. While there is extensive research in each of these areas, the relationship between them is rarely explored. Demographic changes that affect the built environment and the use of natural resources are not currently taken into account. Therefore our ability to inform sustainability and resource decoupling policies is limited. Looking at the population in a more granular manner would allow to better account for lifestyles, cultures, and biophysical characteristics of individuals and their implications for resource use and emissions.

This thesis addresses the linkages between the population and the built environment and presents a mathematical framework for the integrated modelling of demographic metabolism and the socioeconomic metabolism with the aim of improving the understanding of human needs and their consequences for resource use. The framework builds on the premise that an integrated analysis can be based upon the differentiated needs and wants for goods and services among individuals.

The thesis illustrates the framework in the context of an European energy and greenhouse gas reduction policy in the residential sector, a housing deficit policy in Colombia, and a global policy for food-energy demand. Results show that demographic trends and changes in the biophysical characteristics of individuals can play a determining role in the effectiveness of policies – even beyond technological factors. For Europe this means that the same technology-based energy policy can lead to different reductions in energy use and greenhouse gas emissions among member states. For Colombia, this means that delaying actions to close the housing deficit increases the economic and material footprint of the residential sector. However, closing the housing deficit by 2030 as aimed, can lead to a construction industry that grows too rapidly and might be unsustainable in the long term. For global food demand, results depict an additional burden to future food security beyond the mere growth in population size, particularly because of body mass increments in most parts of the world which are partially counteracted by an aging phenomenon.

In conclusion, addressing human needs and wants in resource sustainability modelling implies to explicitly model the differentiated requirements for goods and services of different population segments. In this regard, it is essential to consider that the population stock drives the built environment stocks, and not the other way around. This framework has the potential to provide more accurate and more relevant descriptions and forecasts of infrastructure and resource use resulting from more granular descriptions of the population.

Acknowledgements

This work was carried out at the Department of Energy and Process Engineering and the Industrial Ecology Programme at Norwegian University of Science and Technology (NTNU) in Trondheim, Norway, and during a 2-month research stay at the Colombian National University "Universidad Nacional de Colombia" in Medellín, Colombia. The work has been conducted over a period of 5 years, from 2013 to 2018.

First, I would like to thank my supervisor Daniel Müller for his mentorship all along. I am grateful for the insightful discussions on human needs and the metabolism of our societies. I learned a lot from him. Second, I thank my family, Bernardo, Esperanza and Juan Manuel for all the support in this life changing process, and especially for their encouragement towards the end of my PhD.

I would like to thank all that people that one way or another contributed to this. To my co-authors and friends Yris, Gibran, Amund and Nina, thank you for enriching my research experience. I look forward to many more collaborations. To my close colleagues Eliette, Carine, Cristina, Moana and Magnus, I am grateful for our friendship. To my master students Maren, Pablo, and Avijit, thanks for believing and contributing to the development of this new way of looking at population in SEM, and thank you for being an awesome research team. To my friends in Trondheim, Mirjana, Nico, Gøran, Alejo, Juan David and Mario who were my family in Norway and provided me with unconditional support. To all my students, I owe the best of my PhD to you (IndEcol Master Classes 2013-2016), thank you.

Finally, I must thank Valentina, who above all, made this possible.

Table of Content

List of Appended Papers and Author's Contributions

Paper #	Title	Contribution
Paper 1	Dynamic type-cohort-time approach for the analysis of energy reductions strategies in the building stock. **Vásquez, F.**, A.N. Løvik, N.H. Sandberg, and D.B. Müller. 2016. *Energy and Buildings* 111: 37–55.	Complete literature review, data collection, model development, analysis, visualization and writing. Part of the research design.
Paper 2	Dwelling stock dynamics for addressing housing deficit. Olaya, Y., **F. Vásquez**, and D.B. Müller. 2017. *Resources, Conservation and Recycling* 123: 187–199.	Complete model development and visualization. Part of the research design, literature review, data collection, analysis and writing. First and second author contributed equally to this work.
Paper 3	Food security for an ageing and heavier population. **Vásquez, F.**, Vita, G., and Müller, D.B. (submitted).	Complete research design, data collection, and model development. Part of the literature review, analysis, visualization, and writing. First and second author contributed equally to the literature review, analysis of results, generation of figures and tables, and writing of the manuscript.

1. Introduction

1.1. Development and sustainability: on the relationship between humans, the socioeconomic metabolism, and the environment

Humans perpetually harvest, extract, transform, and use the natural resources to satisfy their needs and wants, while returning to the environment the discards of these processes. We refer to this human-nature relationship as the "socioeconomic metabolism - SEM"[1] or "metabolism of the anthroposphere" (Baccini and Brunner 1991, 2012; Ayres and Simonis 1994; Fischer-Kowalski and Haberl 1998; Fischer-Kowalski et al. 2014).

The type, magnitude and patterns of the appropriated, stocked and emitted resources – matter and energy – are regulated by demographic, social, cultural, economic and technological drivers. Historically, the evolution of these drivers have fostered a continuous increase in the number and quantity of resources appropriated and discarded from and to the environment (Arrow et al. 1995; Krausmann et al. 2008; Fischer-Kowalski et al. 2014; Seppelt et al. 2014).

Today, the human governance of the environment is of such magnitude that many natural cycles (e.g. nutrients and water) and natural regimes (e.g. atmospheric chemical composition, species distribution, forest land coverage) have been altered (Vitousek et al. 1997; Gordon et al. 2006; Gruber and Galloway 2008). The sustainability of humans and other species is now threatened by interrelated issues such as resources availability, food security, climate change, deforestation, and species and ecosystems disappearance (Foley et al. 2005; IPCC 2014). In many environmental aspects we started to exceed the safe operating limits of the planet and its natural capacity for recovery (Wackernagel et al. 2002; Rockstrom et al. 2009).

Yet, worldwide access to resources is uneven, and countries contribute differently to environmental concerns. On the one hand, a large fraction of the world population, especially in developing countries, has insufficient access to the goods and services required to satisfy their needs; including

---

[1] The present thesis conforms to the following definition of Socioeconomic Metabolism (SEM) drawn from the scientific field of Industrial Ecology (Erkman 1997; Ehrenfeld 2000):

> *...the society- nature interactions characterised by material and energy flows and stocks – input of raw materials, processing to manufactured products, services, and release of waste and emissions, including the energy conversion and use. It is determined by the modes of production (economy), the technology, and the lifestyle (culture)"* (Fischer-Kowalski 1998; Fischer-Kowalski and Hüttler 1998; Krausmann et al. 2008).

food, clean water and sanitation, energy, housing, healthcare, education, and transportation (Jahan 2016). On the other hand, with a greater and more egalitarian access to resources, reflected in high living standards, developed countries are major contributors to environmental change, for instance to climate change (Hertwich and Peters 2009; IPCC 2014).

Evidently, current sociometabolic patterns of development are unsustainable (Jackson 2009; Hoekstra and Wiedmann 2014). New patterns are required to overcome unsatisfied needs, inequalities, and environmental problems, especially because of the expected population growth (Lutz et al. 2014a; United Nations, Department of Economic and Social Affairs 2017). In other words, there is a need to decouple well-being and development from resource use and environmental impact (Fischer-Kowalski et al. 2011; von Weizsäcker et al. 2014).

To inform socioeconomic patterns that promote a resource and impact decoupled human development and well-being, it is imperative to have a comprehensive understanding of the relationships between (i) the human population, (ii) the appropriated and transformed resources in the anthroposphere or built environment, and (iii) the natural environment (Figure 1). Ultimately, as previously outlined by Meadows (1998) and by Constanza and colleagues (2007), well-being as an ultimate end relies upon the opportunities (services and goods) that human capital, built capital, and natural capital provide for the satisfaction of people's needs and wants. This means that maintaining certain qualities in each of these capitals in necessary to guarantee the sustainability of the whole system.

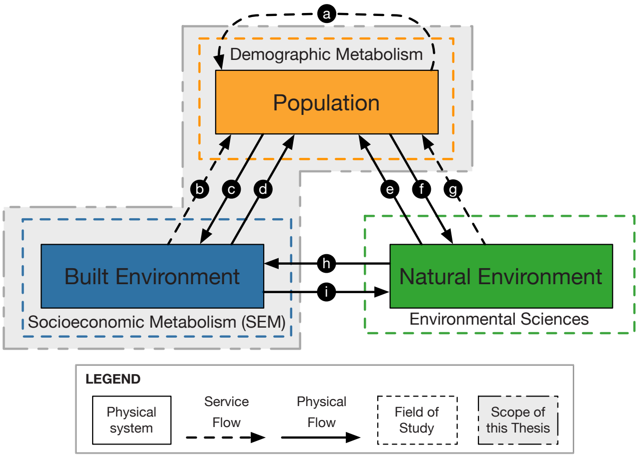


Figure 1. Linkages between the population, built environment and natural environment systems. (a), (b) and (g) represent the services provided to the population by other humans, the built environment and the natural environment respectively. (c) and (f) represent the physical human direct emissions to the built and natural environments (e.g. urine, excreta and breath). (d) and (e) represent the intakes of physical goods by the population (e.g. food, water, and air). (h) represents the resources extracted from nature in order to erect and operate the built environment. (i) represents the emissions to the natural environment.

Despite the evident relationships, these three capitals have usually been studied in isolation by independent disciplines (dashed boxes in Figure 1). Therefore, our ability to inform sustainability and resource decoupling policies is hampered by a limited knowledge of the linkages (arrows in Figure 1) that exist between them. For instance, demographic studies tend to ignore the use of resources by the population or its impact on the environment; studies of the socioeconomic metabolism have so far largely neglected the composition and dynamics of the population and how these shape the built environment; and environmental studies are rarely coupled with the study of the population and the built environment.

The remaining parts of the introduction are structured as follow. Section 1.2 elaborates on the linkages between the population, the built-environment, and the natural environment systems. Sections 1.3 and 1.4 discuss the status-quo of the fields of demographic metabolism and socioeconomic metabolism respectively. Section 1.5 summarises the motivation and scope of the thesis, and section 1.6 presents the research questions and the thesis structure.

1.2. Linkages between the population, the built environment and the natural environment

The linkages between population, built environment, and natural environment systems can be explored at (i) the physical level and (ii) the service level, as described in Figure 1. The physical level refers to the exchange of matter or energy between these systems. The service level refers to all other interactions that do not include a physical exchange.

1.2.1. Physical linkages

Nourishment, hydration and respiration are vital human needs. All of them occur through a physical interaction of the population with the resources from the built or the natural environment. People intake food, water and air[2] for their sustenance (“d” and “e” in Figure 1). These goods are metabolized (i.e. stored, transformed, and discarded) by the body, and the waste from the metabolic processes are

---

[2] Historically, humans have breathed-in (air) directly from nature (the atmosphere). However, as human habitats have grown polluted, purified or processed air starts to supply the respiration needs. A similar process occurred to the drinking water and food. Drinking water used to be taken directly from natural streams and nowadays is provided by a complex infrastructure of aqueducts and treatment plants. Hunters and gatherers took their food directly from nature, yet with the transition towards and agrarian society natural landscapes were transformed into cultivated and grazing landscapes.

released in gaseous, liquid, and solid forms via excreta, urine, breath, and perspiration (“c” and “f” in Figure 1).

A similar interaction occurs between the built and the natural environment. Natural resources are extracted in order to build and operate the man-made infrastructures and goods in the anthroposphere (“h” in Figure 1). Subsequently, discarded resources are returned to the natural environment (“i” in Figure 1). For instance, fossil fuels from the lithosphere and oxygen from the atmosphere are used in combustion processes that result in emission of carbon dioxide and water vapour to the atmosphere.

1.2.2. Service linkages

Humans satisfy some of their needs by making use of the services (or functions) that are provided by the three capital stocks (Meadows 1998; Costanza et al. 2007). For example:

- Education services require teachers (population), school buildings (built environment), and the land (natural environment) where the school rests (“a”, “b” and “g” in Figure 1, respectively).
- Health services need healthcare professionals, a hospital and also land.
- Communication services for people can be provided by mobile phones and the atmosphere for data transmission.
- Recreation services can be provided by the land, water streams and the biota that form the landscape, and hiking trails.
- Shelter is obtained from dwellings and the land where these are built.
- Mobility services require of drivers, vehicles, roads, and land for the roads. The air transport services are provided by pilots, airplanes and the atmosphere.

Physical and service linkages exist between all three capital stocks. This thesis focuses on the analysis of the linkages between the population and the built environment (grey area in Figure 1).

1.3. Demographic metabolism: on the study of the population dynamics

Demography concerns the study of the size, composition, geographical distribution, and characteristics of the population over time (UN 1956; Hartmann 2009; Smith and Keyfitz 2013). The composition is typically expressed in terms of the number of males and females by age or age-groups. Other classifications such as marital status, race, and economic conditions are also used.

Traditionally, population dynamics have been explained by three processes: birth, migration and aging (Schoenbach 2007; Hartmann 2009; Max Planck Institute for Demographic Research 2018). The evolution of the population by sex and cohort is explained by drivers such as birth and fertility rates, death and mortality rates, or migration rates, which are often derived from statistical analyses.

More recently, the theory of demographic metabolism was introduced by Lutz (2012) to explain how societal changes result from the changing composition of the population and its characteristics (e.g. sex, age, life expectancy, educational level, labour force participation). Some of these characteristics might change over the lifetime of a person (e.g. educational level, age) or over generations (e.g. life expectancy, educational level, labour force participation).

Demographic metabolism models have been used to exemplify how changes in education can influence societies' demographic structure (Lutz et al. 2014a) or to investigate the adaptive capacity to climate change (Lutz and Muttarak 2017; Lutz et al. 2014b). Lutz's approach is more comprehensive than traditional approaches. For instance, it considers how education attainment affects the fertility rates and thus the size and composition of the population stock, which in turn has implications for future educational needs.

While the demographic metabolism approach has a high degree of granularity when studying populations, it has not evolved to incorporate the population's physical and service linkages with the built and natural environments.

1.4. Socioeconomic metabolism: on the study of the built environment

The socioeconomic metabolism (SEM) field concerns the study of the built environment, its underlying drivers, and the patterns and magnitude of resources in the anthroposphere (Baccini and Brunner 1991, 2012; Ayres and Simonis 1994; Fischer-Kowalski and Haberl 1998; Fischer-Kowalski et al. 2014). The scope of SEM studies ranges from individual chemical elements (e.g. aluminium, phosphorous) to goods (e.g. dwellings, cars), with varying geographical coverage (e.g. global, regional, national, and urban level) (Cordell et al. 2009; Liu and Müller 2013; Bergsdal et al. 2007;

Pauliuk et al. 2011; Haas et al. 2015; Kennedy et al. 2015). Time-wise, analyses range from one-year to longitudinal exercises that cover several centuries.

The stocks and flows of resources into, out and within the built environment have been studied using material flow analysis approaches based on mass and energy conservation principles (Baccini and Brunner 1991, 2012; Brunner and Rechberger 2005; Hendriks et al. 2000; Müller 2006). The most comprehensive and advanced approaches study the composition of built environment systems by disaggregating the stocks (and flows) across element types (or segments) and according to their cohorts, and following their evolution in time. For instance, studies of the dwelling stock of a nation can differentiate across type of buildings (e.g. single family house, multi-family house) from different construction periods and their corresponding changing material and energy needs (e.g. via renovation) along their service lifetime (Pauliuk et al. 2013; Sandberg et al. 2014, 2016). Thus, these studies depict the diversity of the stock and keep track of the evolution of the resources in the anthroposphere in a consistent and comprehensive manner.

Nevertheless limitations remain when it comes to describing the relationship between the population and their need for resources. Little differentiation of the population across segments and cohorts has been used in studies of the socioeconomic metabolism. Typically, the population is only considered in terms of its size, while other demographic characteristics are neglected (e.g. sex, age, economic condition or educational attainment). This limits the analysis of changing infrastructure and resource demand as a consequence of population aging, generational renewal, or changes in other demographic characteristics. Hence, existing SEM models are not suitable to address issues such as the need for elderly care facilities or kindergartens and schools, which are determined by the aging and reproduction processes of the population.

Although several authors have pointed out the need for integrating sociodemographic analysis in SEM studies (Krausmann et al. 2008; Fischer-Kowalski et al. 2011), very little quantitative research has been conducted so far in this direction. For instance, Hu and colleagues (2010a, 2010b) have segmented a country's population in the context of resource use. Their approach explored the Chinese housing dynamics and their implications for iron and steel given the dynamics of the urban and rural population. However, only the total population for the urban and rural areas is considered in disregard of their cohort and sex structure. Thus, they only conclude on the average dwelling floor area per capita and the average amount of materials for each population segment.

Overall, the repercussions on the composition and dynamics of the built environment stocks arising from sociodemographic changes and differences within and across societies have not been explored. Looking at the population in a more granular manner would allow to better account for lifestyles, cultures, and biophysical characteristics (e.g. age, sex, weight) of individuals and their implications for resource use and emissions.

1.5. Motivation and scope

This thesis explores both the physical and service linkages between the population and the built environment. It builds on the postulate that the needs and wants for goods and services change across societies and cultures, across people of different age and sex, and along the lifespan of a person (Max-Neef et al. 1991).

The linkage at the physical level is investigated using a case study on food. The linkage at the service level is studied with two cases on housing; one in the context of energy and climate change, and a second one in the context of housing deficits. In the following subsections, we elaborate on the importance and challenges of food and housing that motivate the demographically-extended SEM framework developed in this thesis.

1.5.1. Physical linkage: the case of food

Food security is a major global concern (FAO et al. 2015). Ending hunger and granting adequate nutrition for everyone is one of the 2030 sustainable development goals (UN General Assembly 2015). In relation to this goal, most of the research on food security focuses either in the food production processes or losses across the value chain (Tilman et al. 2011; FAO 2011; Rayfuse and Weisfelt 2012; Shafiee-Jood and Cai 2016; Xue et al. 2017). Food demand tends to be represented by average consumption per capita expressions that do not address the distinct food requirements of people of different ages and biophysical characteristics. Ultimately, this limits opportunities to formulate regional strategies tailored to specific demographic conditions. Only few studies have been conducted on consumer needs as a function of demographic changes through time (Hiç et al. 2016).

The food requirements of a person, specifically the food-energy needs, depend upon biophysical characteristics, including age, sex, and weight (United Nations University et al. 2001). For example, the food-energy needs of a male are larger than those of a female of the same weight and age. Alternatively, in people of the same sex but of different age and/or weight the food-energy needs are also different. While weight increments lead to higher energy requirements, ageing reduces these requirements. Thus, the food-energy requirements can be described as a function of demographic, cultural, and biological processes.

Cohort-wise, there have been increases in height (NCD Risk Factor Collaboration (NCD-RisC) 2016) and body mass (NCD Risk Factor Collaboration 2016) in the last century, both leading to increases in weight. At the same age, younger generations tend to be taller and heavier than older ones. Moreover, a worldwide aging phenomenon has been observed (Lunenfeld 2008; Lee and Mason 2011; Lutz et al. 2008). Both conditions, along with population growth (Lutz et al. 2014a; United Nations, Department of Economic and Social Affairs 2015; Gerland et al. 2014), have repercussion for food demand. The impact of these drivers on food demand has yet to be explored in a systematic way.

1.5.2. Service linkage: the case of housing

The residential sector faces different challenges worldwide. First, dwellings are a major consumer of materials and energy and consequently a major contributor to climate change (Lucon et al. 2014). Second, there is still a large fraction of the world population living in slums and inadequate dwellings (UN-Habitat 2003, 2012, 2016). Accordingly, the 2030 sustainable development goals concern the resource efficiency and mitigation of climate change in the sector, as well as ensuring adequate, safe, and affordable housing for all (UN General Assembly 2015). In addition, regional and national specific goals have been set, along with policies for their achievement.

For instance, in terms of greenhouse gas emissions, the residential sector in Europe is set to achieve reductions close to 90% with respect to 1990's levels by 2050 (European Commission 2011). This target has been aligned with policies that establish strict energy performance of new and refurbished buildings (European Parliament and The Council of The European Union 2010, 2012).

In terms of adequate housing, Colombia has the challenge of providing appropriate shelter to the population living in slums, estimated to be 13% in 2014 (UNSD 2015), and to the households in housing deficit, estimated to be 36% in 2005 (DANE 2005). Several policies have been developed to address the housing deficits, including enabling access to loans, subsidising housing loans' interest rates, and providing free dwellings (Bouillon et al. 2012; Murray and Clapham 2015; Gilbert 2014). The latest of these policies provided 100 000 free dwellings between 2014 and 2018.

Nevertheless, in Europe and in Colombia, the policies have been designed without the support of models that consider the demographic and housing dynamics, and that enable policy makers to evaluate the effectiveness of alternative strategies to achieve the goals. For example, in the case of European Union, where countries have different population trends, it is unclear if the same policies will deliver the same results in each member state.

It is known that the population and housing trends are different across countries (United Nations Department of Economic and Social Affairs 1974, 1976, United Nations Department of International Economic and Social Affairs 1980, 1985; UN and UN 1995; United Nations Department of Economic and Social Affairs and United Nations Centre for Human Settlements 2001). Some EU member states have a growing population while others are experiencing a population decline. Likewise, housing trends have changed over time and are different across countries in the world. The average living area has risen while the number of people per dwelling is declining. These changes have a direct effect on the need to expand, reduce, or adapt the dwelling stock. However, these linkages have not been evaluated in studies.

1.6. Research questions and thesis structure

The integration between the demographic metabolism and the socioeconomic metabolism can help formulate more effective policies that aim to manage the relationship between population, infrastructures, and resource use. The demographic metabolism approach can be used to represent the population and their needs and wants in a consistent and coherent manner, while the socioeconomic metabolism approach can represent the resources employed in satisfying those needs.

This thesis presents a new framework to address the physical and service linkages between the population and the built environment with the aim of improving the understanding of human needs and their consequences for resource use. In this context, the following four research questions were formulated:

i. How do changes in population, housing service demand, and building technologies affect the options to reduce energy use and greenhouse gases emissions in the residential sector?
ii. How do socioeconomic differences and demographic trends affect the options for eliminating housing deficits and reducing housing service inequalities?
iii. How do changes in demography and human's biophysical characteristics affect food energy demand and food security strategies?
iv. How can socioeconomic metabolism and demographic metabolism be integrated using a common mathematical framework?

The first three questions are addressed in three independent papers, which progressively present and develop a framework towards the integrated modelling of the socioeconomic metabolism and the demographic metabolism concerned in question (iv). Questions (i) and (ii) relate to the service linkage between the population and the built environment, while question (iii) relates to the physical linkage. The order of the papers follows the chronological progress of the work and are appended at the end.

Paper 1 studies the energy demand and dynamics of the residential sector in developed – European – countries. Paper 2 concerns housing deficits - inadequate housing and slums – and construction in developing countries. Paper 3 studies the changes in food-energy requirements of the world adult population in relation to its demographic and biophysical changes.

Methodology-wise, all papers build on the same modelling approach to dynamic stock-flow modelling introduced in Paper 1 (see Chapter 2 on Methodology), hereinafter the Type-Cohort-Time (TCT)[3] approach. Paper 1 uses this approach to track the evolution of the stock of different types of dwellings according to their cohorts (construction years). While in Paper 1 the population remains described only in terms of size, Paper 2 extends the TCT differentiation to households and dwellings – by type of housing quality condition. Paper 3 uses the TCT approach to account for the age-sex-nationality structural differences of the population regarding food needs.

---

[3] The term "Type-Cohort-Time" was used by Vásquez and colleagues (Vásquez et al. 2016) to describe the different dimensions employed in models and studies of the energy use in the building stock. Similar terms have been used before to describe similar aspects (dimensions) of stocks, for instance "type-age" (Brattebø et al. 2009) or "segments" (for dwelling types and construction periods) (Sandberg et al. 2014).

The rest of the thesis is structured as follows: Chapter 2 presents the methodological basis. Chapter 3 summarises the scope and main findings of each paper. Chapter 4 discusses the findings in light of the research questions.

2. Methodology: Demographically-Extended Socioeconomic Metabolism

Both population and built environment can be regarded as dynamic and heterogeneous systems consisting of elements (individuals or processes) and their interactions (flows in terms of people or goods). The processes can be grouped into different types and cohorts with changing characteristics. Both systems are open, with inputs (e.g. immigration, or import of goods) and outputs (e.g. emigration, or export of goods). Accordingly, demographic approaches and socioeconomic metabolism approaches use similar principles and techniques to explain the composition and evolution of the systems. This thesis builds upon these similarities and presents a multidimensional mathematical framework, namely the Type-Cohort-Time (TCT) approach, for the integrated modelling of the stock and flow dynamics of the population and the built environment.

We introduce the TCT by using a system definition (Figure 2, Figure 3 and Figure 4), and a system of discrete difference-equations, consisting of balance, intrinsic and model approach equations. Firstly, in the context of socioeconomic metabolism modelling in section 2.1. Secondly, in the context of demographic modelling in section 2.2. And thirdly, as a mean to integrate demographics in SEM models in section 2.3. This system of balance, intrinsic and model approach equations is common in SEM approaches. Demographic approaches do not use the same categorisation, yet their equations can also be expressed in the same way, allowing for a common framework to integrate the two.

For built environment resources we use the symbols "**j**" for types and "**k**" for cohorts. For population, we use the symbols "**i**" and "**c**" to refer to types and cohorts respectively. The symbol "**t**" refers to time. The notation for the variables and parameters used in demographic and SEM modelling are presented in the corresponding sections.

2.1. Socioeconomic Metabolism Modelling

Figure 2 presents a system definition for the study of the stock and flows of a physical resource in given region. Three variables are considered: Stock (**S**), Inflow of New Elements (**N**) and Outflow of Old Elements (**O**).

The equations that explain each of the variables or the relationship among them are drawn from quantitative approaches to study the socioeconomic metabolism which follow the modelling principles to Material Flow Analysis (MFA) (Baccini and Brunner 1991, 2012; Hendriks et al. 2000; Müller 2006; Pauliuk et al. 2013). Hence, this section does not intend to provide a complete description of all phenomena in the socioeconomic metabolism, but instead it illustrates the basic principles for modelling built environment systems.

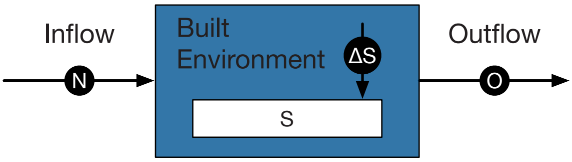


Figure 2. Typical built environment system definition. S and ΔS represent the stock and its stock change respectively. Arrows represent flows.

2.1.1. Balance Equation

The balance equation links the flows with the change in the stock. Thus, the stock change (**ΔS**) at the end of a given year “**t**” results from balancing the new incoming elements (**N**) and the outflow of old elements (**O**) in the year (Eq. 1).

$$\Delta S_t = N_{t=k} - O_t \qquad \text{(Eq. 1)}$$

For the new elements (**N**), the year “**t**” when they enter the system corresponds to their cohort year “**k**”, thus “**t=k**”.

2.1.2. Intrinsic Equations

This type of equations describe the links between the stock, stock change and flows using their intrinsic properties. For instance, the stock of two different years can be linked through the stock change (Eq. 2).

$$S_t = S_{t-1} + \Delta S_t \qquad \text{(Eq. 2)}$$

It must be noted that stocks of the built environment are composed of elements from different cohorts “**k**” that can also belong to different types “**j**” (Eq. 3). Thus, both types and cohorts can be differentiated in all modelling equations. For instance, the balance equation can describe the stock change as the sum of the inflows and outflows of different type-cohort segments (Eq. 4).

$$S_t = \sum_j \sum_k S_{j,k,t} \qquad \text{(Eq. 3)}$$

$$\Delta S_t = \sum_j N_{j,k=t} + \sum_j \sum_k O_{j,k,t} \qquad \text{(Eq. 4)}$$

2.1.3 Model Approach Equations

Model approach equations link the system variables (stock or flows) with the system drivers (parameters). Because a given system can be modelled assuming different drivers, there are multiple ways to define model approach equations.

Here, we present an example to explain the outflow (**O**) of elements of a specific type "**j**" and cohort "**k**" in a year "**t**", given the inflow (**N**) of these elements in their cohort year "**k**", and a lifetime probability (**LT**) that explains the elements' likelihood to leave the stock according to their age[4] (Eq. 5). Accordingly, the total outflow of a year is the sum of the outflows from different cohorts (Eq. 6)

$$O_{j,k,t} = N_{j,k} \cdot LT_{j,k,t} \qquad \text{(Eq. 5)}$$

$$O_t = \sum_j \sum_k N_{j,k} \cdot LT_{j,k,t} \qquad \text{(Eq. 6)}$$

2.2. Demographic Modelling

Figure 3 presents a system definition for the study of the population stock and flows in a given region. Five variables are considered: Population Stock (**P**), Births (**B**), Deaths (**D**), Immigration (**I**) and Emigration (**E**). Immigrants (I) and Emigrants (E) are flows of people coming from and going to another regions respectively. Births (B) are not a physical flow of people since new-born babies do not come from somewhere else but stem from the population. Similarly, Deaths (D) are not a physical flow but a change of state. Thus, births and deaths can be seen as sources and sinks. For reasons of simplicity, they are represented as flows.

---

[4] The age of an element is the year of analysis "t" minus its cohort year "k".

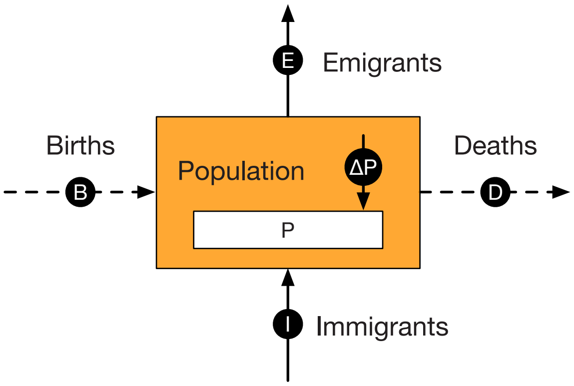


Figure 3. Typical demographic system definition. P and ΔP represent the population stock and its stock change respectively. Arrows represent flows. Solid arrows depict physical flows of people from and to another region. Dashed arrows are sources and sinks of people illustrated as flows for simplification.

The equations that explain each of the variables or the relationship among them are not specific to one demographic method, instead they are our own generalisation from different approaches found in literature (UN 1956; Schoenbach 2007; Becker 2008; Hartmann 2009; Smith and Keyfitz 2013). The method that we present does not intend to provide a complete description of all demographic phenomena, but instead to communicate the essentials of demographic modelling and to illustrate the use of a common mathematical language with socioeconomic metabolism modelling.

For the most part we use widely accepted terms in demography and we adapt and present other terms in a more generic way due to the variation of notation in the field (Hartmann 2009).

2.2.1. Balance Equation

In a region, the population change (**ΔP**) at the end of a given year "**t**" is the result of balancing the births (**B**), deaths (**D**), immigrants (**I**) and emigrants (**E**), using the so-called demographic or population balancing equation (Schoenbach 2007; Becker 2008; Land et al. 2005) (Eq. 7).

$$\Delta P_t = B_t - D_t + I_t - E_t \qquad \text{(Eq. 7)}$$

2.2.2. Intrinsic Equations

The population stock of two adjacent years is linked through the stock change (Eq. 8).

$$P_t = P_{t-1} + \Delta P_t \qquad \text{(Eq. 8)}$$

Because the population stock is composed of individuals of different sex “**i**” from different cohorts “**c**” (Eq. 9), all system variables can also be expressed in terms of the different sexes and cohorts as shown for the balance of stock of the year in Eq. 10.

$$P_t = \sum_i \sum_c P_{i,c,t} \qquad \text{(Eq. 9)}$$

$$\Delta P_t = \sum_j B_{j,c=t} - \sum_j \sum_c D_{j,c,t} + \sum_j \sum_c I_{j,c,t} - \sum_j \sum_c E_{j,c,t} \qquad \text{(Eq. 10)}$$

2.2.3. Model Approach Equations

The system variables can be calculated in multiple ways since there exists diverse driving parameters and methods to explain the same demographic phenomena. The model approach equations presented here are examples that reflect the general logic followed in different approaches.

The total number of births in a year “**t**”, which correspond to the cohort year “**c**”, depends on the stock of women “**i=women**” of each cohort and their cohort-specific fertility rate (**FR**) (Hartmann 2009) (Eq. 11). This rate represents a woman’s probability to have children, which vary along her lifespan, and that can be different across women of different cohorts.

$$B_{c=t} = \sum_c P_{i=women,c,t} \cdot FR_{c,t} \qquad \text{(Eq. 11)}$$

The probability of dying is also a function of the age of a person and can vary across cohorts along with changes in the life expectancy (Schoenbach 2007; Hartmann 2009). Therefore, deaths are estimated using a death or mortality rate (**DR**) (Eq. 12).

$$D_t = \sum_i \sum_c P_{i,c,t} \cdot DR_{i,c,t} \qquad \text{(Eq. 12)}$$

Finally, immigration and emigration can also be estimated from migration rates (UN 1956), in a similar fashion as for births and deaths.

2.3. Demographically-Extended Socioeconomic Metabolism Modelling

Figure 4 presents a system definition for the integrated study of the stocks and flows of population and resources in the built environment. Population (**P**) and built environment (**S**) stocks are linked through needs and wants of the people for goods and infrastructures (**A**), either for their intake (physical linkage) or service use (service linkage).

The need or want for a certain type "**j**" of stock (of certain cohort "**k**") can differ among people of different cohorts "**c**" and population types "**i**" – sex, culture, lifestyle, or socioeconomic conditions. Hence, the total demand for that specific stock is the sum of the individual demands across population type-cohort segments. This can be expressed by model approach equation (Eq. 13) that explains how the population drives the built environment stocks.

$$S_{j,k,t} = \sum_i \sum_c P_{i,c,t} \cdot A_{j,k,t} \qquad \text{(Eq. 13)}$$

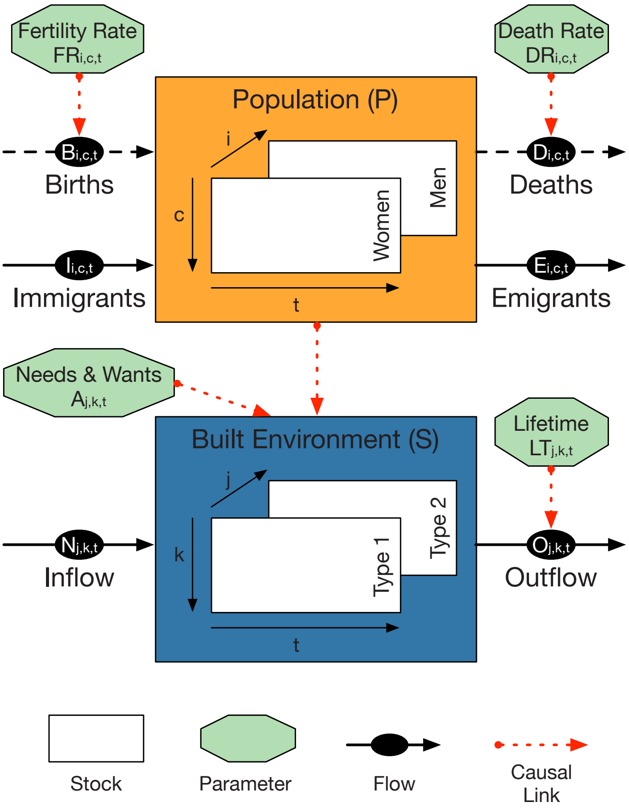


Figure 4. System definition for a demographically-extended socioeconomic metabolism analysis. (i) and (j) represent types in the population and built environment respectively. (c) and (k) refers to cohorts. (t) stands for time.

The modelling framework, summarised in Figure 4, was not the starting point for the thesis. Instead, it was gradually developed throughout the thesis. Hence, Paper 1 did not apply the full framework, but rather focused on the dynamics of the built environment systems. Paper 2 progressed the framework to integrate the population dynamics at the level of households with those of the built environment. Paper 3 applied the framework for the population only but a higher degree of granularity than Paper 2.

3. Summary of Papers

3.1. Paper 1

In this paper (Vásquez et al. 2016), a Type-Cohort-Time (TCT) approach for stock dynamics modelling is presented and applied for the study of energy reduction strategies in the residential sector of Germany and Czechia[5]. The need for dwellings is described in terms of the average living area per inhabitant, the population size, and the preference for a dwelling type. The Type-Cohort (archetype) differentiation was applied to four types of dwelling-buildings (single family houses, multi-family houses, terraced houses, and apartment blocks) to estimate their energy requirements (for heating and hot water) along their life.

It was found that the same policies on energy reductions can lead to different results in each country given the distinct (i) population trends, and (ii) structure (age and type distribution) and level (size) of development of the stock. Germany has a declining population that naturally reduces the need for energy and for new buildings. However, it has a more mature (older and larger) stock, which results in higher replacement and renovation requirements. This limits the effectiveness of policies that promote energy reductions in new construction, and brings the attention to the renovation activity. On the other hand, Czechia exhibits a younger stock that calls for expansion given the growing trends on population and average area per capita. Thus, strategies that promote energy efficiency gains in new dwellings are imperative to avoid locking into young but highly energy-demanding dwellings.

Methodology-wise, this paper demonstrates that dynamic building stock models that differentiate across types and cohorts are an effective tool to bridge the gap between the energy reduction targets required to achieve climate goals and the policy tools deployed to achieved them.

3.2. Paper 2

In this paper (Olaya et al. 2017), the TCT approach is used to study scenarios for closing the housing deficits of Colombia. Three types of housing conditions are considered – No Deficit, Qualitative Deficit, and Quantitative Deficit – which reflect (i) the living arrangements of households (i.e.

---

[5] Czech Republic at the moment of the study was conducted.

number of households per dwelling), and (ii) the conditions of the dwelling. The “No Deficit” relates to the optimal condition where one adequate dwelling is inhabited by one household only. The “Qualitative Deficit” condition reflects a dwelling that needs improvements which is inhabited by one household. The “Quantitative Deficit” relates to the condition where one inadequate dwelling (needs to be replaced) hosts one or more households. Commonly, non-deficit dwellings are built through formal construction processes and accessed by the middle and upper-income classes of the society. Dwellings in deficit are self-built by the low-income segment of the population.

Accordingly, the TCT approach was tailored to concurrently model the dynamics of the households and the dwellings since deficits reflect the status of both. The need for dwellings is described in terms of the number of households per dwelling and the number of people per household given a certain distribution of households across deficit types which reflects the socioeconomic conditions of the population. Nine socioeconomic scenarios were analysed for closing deficits by 2030, 2050 and 2090.

The findings reveal that closing deficits by 2030 is accompanied by the challenge of increasing current construction activity by 97-155% in the short-term with subsequent shrinkage to present levels once the problem is solved. On the contrary, if mechanisms to solve the housing deficit situation are not implemented, between 0.5 and 1.6 million additional households will be in deficit by the same year; which is around 10-30% more than today. Although demographic decline can reduce both the number of households with deficit and the construction efforts for closing deficits, it is not sufficient to solve the problem and interventions are required. Conversely, regardless of the demographic scenario, delaying actions increases construction required to close the gap.

Here, it is demonstrated that policies for closing housing deficits need to be based on knowledge of demographic and dwelling stock development and their linkages. Furthermore, it is demonstrated that dwelling stock models can be integrated with household stock models in order to analyse and promote strategies for reducing inequalities that relate to the built environment.

3.3. Paper 3

This paper applies the TCT approach to investigate the changes in food-energy demand due to changes in the demographic structure and in the biophysical characteristics of the world’s adult population between 1975 and 2014. The population stock is differentiated by sex and cohort, and the body mass index and height are used to estimate the caloric demand of individuals according to their sex and age.

It was found that the global food energy requirements increased by 129% over the past four decades. Population growth contributed with 116% of this increment, weight and height gains with 15%, and the aging phenomenon counteracted the rise by 2%. Today's average human is 14% heavier, 1.3% taller, 6.2% older, and 6.1% more energy demanding than his counterpart in 1975. The results depict an additional burden to future food security beyond the mere growth in population size, particularly because there is a trend towards body mass increments in most parts of the world. Yet, it needs to be explored how much the aging phenomena can counteract this burden.

This paper demonstrates that the same approach used for modelling built environment systems can be employed to address the population system and its physical linkage with resources. Using a demographically explicit stock-dynamics approach to population for addressing food issues goes beyond food security and could potentially include food waste reduction strategies, and waste and recycling strategies.

4. Discussion and conclusion

4.1. Question (i)

informing options to reduce energy use and greenhouse gas (GHG) emissions in the residential sector considering changes in population, housing service demand, and building technologies

Opportunities to reduce energy use and GHG emissions in the housing stock are determined by the interactions between (i) the dynamics of the population, (ii) the type of dwellings and living area demanded by the population (the housing service demand), and (iii) the energy performance of different dwelling types of different construction periods (building technologies). These three factors vary across and within countries. Accordingly, same technologically-oriented energy and climate policies are expected to deliver different results in different regions.

The size of the population and the living area per capita determine the size of the stock at a given year. The preference for a type of dwelling affects the stock composition. The building technologies determine the energy efficiency and energy sources of different dwelling archetypes (types and cohorts). These drivers interact altogether in the context of construction (introduction of new dwellings), refurbishment (improvement of existing dwellings), and demolition (removal of old dwellings) activities to shape the dwelling type-cohort composition of the stock and its related energy use.

We demonstrate that MFA models provide a comprehensive framework to evaluate the effectiveness of strategies for reaching energy and climate targets, considering population, service demand, and technological drivers. As a result, regional priorities can be set for the implementation of policies that deliver best energy and GHG reductions in the context of each country as demonstrated for the cases of Czechia and Germany. In simple terms, it allows to identify when and which policies will have a greater impact.

For example, a growing population trend coupled with a growing average living area per capita, such as the one forecasted for Czechia, calls for the rapid expansion of the standing dwelling stock. This makes the introduction of less energy demanding dwellings in new constructions an efficient strategy to achieve overall energy reductions in the near future. Besides, following this expansion and the relatively short lifetime of existing buildings, the relative share of old and energy-intensive buildings is shrinking, which makes refurbishment initiatives less effective for overall country-level energy reductions.

In contrast, a declining population, such as the one Germany is already experiencing, is enough to counteract the growing dwelling size per capita, and calls for a shrinkage of the total stock. This results in increasing vacancy and organic reductions in the energy demand and the construction activity. These trends coupled with a relatively long lifetime of existing dwellings make refurbishment activities more relevant for overall energy reductions, while limiting the opportunities to introduce new and more energy-efficient dwellings.

Under the current European framework (European Commission 2011), which sets energy reduction targets as percentage of a baseline energy use at the country level, the population dynamics play a larger role than the service demand and the building technologies. For the cases studied in Paper 1, the population decline in Germany conduces to achieving the national energy goals without the need of decreased living standards or large efforts in refurbishments. On the contrary, the growing population of Czechia, which is also demanding larger houses each year, requires deeper and more immediate technological measures to achieve the same energy goals.

Current European policies (European Parliament and The Council of The European Union 2010, 2012) focus on interventions at the building level (e.g. zero energy buildings and deep energy renovation) in order to achieve the country-level energy reduction goals. Yet, we demonstrate that these technological-oriented policies might not be sufficient on their own for achieving the targets, given current demographic and service demand trends. Thus, changes in energy-related user behaviour are also required. The TCT approach could be used to analyse the influence of the users in the total energy use in a systematic way. For instance, by accounting for the specific energy demand of people from different population segments and their likelihood towards adopting energy saving habits and measures.

4.1.1. Methodological reflection

The dynamic Type-Cohort-Time TCT approach presented in this thesis (in Paper 1) enables the study of the long-term *"construction-demolition-refurbishment"* interactions that shape the size, composition and energy requirements of the dwelling stock – by type and cohort. It uses the population, the service demand and building's technology and lifetime as drivers.

The TCT approach expands the *Cohort-Time* modelling principles employed in previous studies (Müller 2006; Sandberg et al. 2011; Sandberg and Brattebø 2012; Hu et al. 2010a) by adding *Type* as an additional modelling dimension which enables the study of dwellings' characteristics that are not common to each element to the stock but that are type-cohort dependent, e.g. the energy needs of a building or its material composition. Thus, the TCT approach opens a path for dynamic stock models to move from a mere description of general characteristics of the total stock or certain cohorts, towards a more comprehensive and disaggregated description of the characteristics of its elements, while still keeping the account on the totality of the stock. This allows to identify potential resource-related bottleneck or opportunities for certain segments of the stock, which ultimately adds relevance to policy making. This type of analysis is particularly important in the context of climate-energy mitigation, where possibilities for energy gains might depend on the technological options for new buildings or the refurbishment existing buildings of different typologies.

4.2. Question (ii)
informing options for eliminating housing deficits considering socioeconomic differences and demographic trends

Housing deficits, understood as the lack of sufficient adequate dwellings in a country, are defined by the socioeconomic conditions of households and the demographic aspects related to population size and households size. These factors are country-specific, hence, the policies required to solve the problem must also be specifically tailored to the conditions of each country.

Factors such as income, purchasing power, and access to financial markets vary across type of households and affect the type of dwelling they access, and whether several households must share a dwelling. The demographic trends (growth or decline), in combination with the household size trends, determine the total number of households. The interaction between these factors regulates the size and composition of the housing stock in regards to the adequacy and sufficiency of the dwellings.

We show that a TCT approach provides a suitable framework to integrate the modelling of household dynamics and dwelling dynamics in order to inform country-specific policies aiming at reducing housing deficits. The framework considers the demographic particularities and type segmentation of the households as well as the type and cohort segmentation and dynamics of the dwelling stock. This allows to evaluate the effectiveness of different policy interventions as well as to generate information on the magnitude of interventions (e.g. construction of new dwellings) required to close deficits in different time horizons, as explored for the case of Colombia in Paper 2.

Since dwellings with deficits are typically self-built by households with low income, there is an explicit need for interventions that promote the improvement of their economic conditions so these households can access a new dwelling of adequate conditions. Accordingly, the earlier the interventions the better in terms of material and economic resources. Early interventions will avoid the construction of more inadequate dwellings, which eventually need to be replaced by adequate dwellings.

Yet, as observed for Colombia, promoting a rapid access to adequate dwellings implies a sudden and significant expansion of the construction activity that will cease once the problem is solved. This might have significant economic repercussions for the construction sector. These repercussions need to be analysed together with the socioeconomic implications resulting from a delay of actions to solve the housing deficits.

Policies oriented towards eliminating housing deficits and slums need to consider not only current deficits indexes, but also the possible growth (expansion) of the inadequate dwelling stock in the future resulting from the households dynamics. In this sense, it is not enough to use conventional forecasts on the population size such the one used in Paper 1, but it is also necessary to take a household stock approach to the problem.

So far we have used the same average number of persons per household regardless of housing type. This might yield over/under estimation of the need for dwellings in certain segments of the population since there are possibilities of having distinct household sizes across households types. The TCT approach can be tailored to address these type specificities.

4.2.1. Methodological reflection

The same Type-Cohort-Time approach employed in the study of dwellings (in Paper 1) could in theory be used to capture the dynamics of households, with some adaptations. Unlike dwellings, which are made out of materials that come from the natural environment, the households are arrangements of the population stock. Thus, their elements are not coming from outside the system, but instead, households are created and destroyed by the individuals forming the population stock. Thus, when dealing with households, it is necessary to account for the dynamics of the population stock and the dynamics in the size of the household unit. Accordingly, the models need to be tailored to only account for the intrinsic changes of the household arrangements instead of accounting for inflows or outflows to the stock as commonly done for stocks of the built environment.

A further model adaptation is required compared to conventional dwelling stock models where dwellings commonly preserve their type until the end of their useful lifetime. Households can change their socioeconomic conditions in desirable (decrease of inequalities and higher income) or undesirable (increase of inequalities and lower income) ways, implying a change in their type. Thus, flows across household types are required to be taken into account. Moreover, these changes in household type could imply the physical upgrades of a dwelling, which makes necessary to account for dwelling type changes as well.

4.3. Question (iii)

informing food security strategies considering demographic changes and changes in the biophysical characteristics of humans

Food-energy requirements depend on people's age, sex, weight and physical activity level. Thus, the total food requirements of a region depends upon its demographic composition, and the biophysical and lifestyle characteristics of its individuals. Accordingly, long term food security strategies are best informed by a comprehensive understanding of the long term food demand variations due to demographic and evolutionary processes of the population.

A TCT approach as the one used for the energy requirements of dwellings in Paper 1, is suitable for the longitudinal study of the energy metabolic requirements of humans. The human body acts as an infrastructure: it requires physical resources for its growth and sustenance (operation). From this physical perspective, the population stock is similar to a built-environment stock; it is constituted by individual elements with resource – energy – requirements that depend upon characteristics that relate to the cohort and the sex (or type) of the individuals, as explored for the food energy requirements of the world adults in Paper 3.

We found that the adults' food energy demand has increased by 129% in the last four decades. The increase in population numbers remains to be the main reason for this (116%). Yet, across generations there has been a tendency towards the growth of individuals - in height and weight – that have significantly contributed to the increase of food requirements (15%). On the contrary, the aging population phenomenon has partially counteracted the increase in food demand (-2%).

If the observed trends continue, food energy demand worldwide will continue to grow beyond the increase in population numbers, mainly due to the almost generalised upward trend of body mass and height in individuals across nations. Thus, on the average, food demand per capita will continue to increase; calling for an expansion of the food production and processing systems.

4.3.1. Methodological reflection

The TCT model for the study of the population energy requirements is similar to the model employed in the study of energy demand in the built environment. The accounting of the population differentiated sex and cohorts similar to the dwelling stock, which differentiated types and cohorts. Furthermore, people's attributes such as height and weight can be treated analogously to the dwelling's attributes such as area or volume. Thus, similar model approach equations can be used to relate the stock to a type-cohort specific energy demand factor.

4.4. Question (iv)
on the demographic extension of socioeconomic metabolism methods

Both, the built environment and the population are dynamic stocks constituted of elements grouped into different types and cohorts with different characteristics that can change over time. For instance, the residential stock is made up of single dwellings with area, volume, and material composition that can change during their useful life or across dwelling types and construction techniques and periods. In the same manner, the population is composed of individuals of different ethnicities, age, and sex whose characteristics change along their life and across cohorts, such as height, weight, life expectancy, beliefs, culture, educational attainment, and economic condition.

Similarly, the change in physical characteristics of a dwelling (e.g. via refurbishment) has energy and material implications in a similar manner that the change in weight and height of humans have implications for food demand (energy and mass). Furthermore, for both stocks, every year, new cohorts are introduced (e.g. births and new constructions), and outflows are discounted (e.g. deaths and decommissioning of infrastructure).

These common properties allow to represent the composition and evolution of both population and built environment stocks using a TCT approach, which in turn enables to address the physical and service linkages that exist between these two systems under a common mathematical framework. Since both stocks have similar structures, they can be described using a set of balance, intrinsic, and model approach equations. Balance and intrinsic equations are in both cases applied to describe the relationships between stocks and flows, while differences appear in the model approach equations because the drivers of these system are different. In this regard, it is essential to explicitly consider that the population stock is driving the built environment stocks, and not the other way around.

This thesis illustrates that a TCT approach is suitable for the study of the heterogeneity and dynamics of both type of stocks, either in isolation (Papers 1 and 3) or in conjunction (Paper 2). In Paper 1 and Paper 3 we showed how a TCT approach can be used to study energy requirements in the dwelling stock and the population stock respectively. Paper 2 illustrates how both stocks can be integrated into the same model to study the service linkage between the population and the built environment. Paper 3 is a first step towards a complete description of the physical linkage with the anthropogenic food resources.

4.5. Conclusion and outlook

The notion of sustainability rests on the premise of adequately meeting the needs of the present population without compromising the ability of future generations to meet their own (World Commission on Environment and Development 1987). Thus, resource sustainability strategies must be informed by a thorough understanding of the human needs and the associated resource use. The linkage of the demographic metabolism and the socioeconomic metabolism is an important cornerstone for this.

Addressing human needs and wants in resource sustainability modelling implies to explicitly model the differentiated requirements for goods and services of different population segments. The framework that this thesis presents has the potential to provide more accurate and more relevant descriptions and forecasts of infrastructure and resource use resulting from more granular descriptions of the population and needs.

For instance, the demand for healthcare facilities and personnel can be studied in relation to the ageing and life expectancy changes of the population. The need for schools and teachers can be analysed in connection to the population's fertility and birth rates, and the changing educational attainment across generations. The need for clothing and food can be examined through the lens of the changing biophysical characteristics of the individuals across generations and along their lives. The housing preferences and energy use behaviour of different population segments can be also investigated in a similar manner.

This work demonstrates that the same mathematical framework can be used to the description of both resources in the anthroposphere and the population, enabling their integration. This approach promotes a more refined study of the goods and services provided by the population and built and natural resources for the satisfaction of needs and wants.

References

Arrow, K., B. Bolin, R. Costanza, P. Dasgupta, C. Folke, C.S. Holling, B.O. Jansson, et al. 1995. Economic growth, carrying capacity, and the environment. *Science* 268(5210): 520–521. http://www.scopus.com/inward/record.url?eid=2-s2.0-11944250828&partnerID=40&md5=ddeb916e1d16434b5e4dd4f9da58e8ef.

Ayres, R.U. and U.E. Simonis. 1994. *Industrial metabolism : restructuring for sustainable development*. Tokyo [etc.]: United Nations University Press. http://edepot.wur.nl/75761.

Baccini, P. and P.H. Brunner. 1991. *Metabolism of the anthroposphere*. Berlin: Springer-Verlag.

Baccini, P. and P.H. Brunner. 2012. *Metabolism of the anthroposphere: analysis, evaluation, design*. MIT Press.

Becker, S. 2008. Population Change and Projection. *Course: Introduction to Demographic Methods*. http://ocw.jhsph.edu/courses/demographicmethods/PDFs/idm-sec11.pdf.

Bergsdal, H., H. Brattebø, R.A. Bohne, and D.B. Müller. 2007. Dynamic material flow analysis for Norway's dwelling stock. *Building Research & Information* 35(5): 557–570. http://dx.doi.org/10.1080/09613210701287588.

Bouillon, C.P., N. Medellín, and C. Boruchowicz. 2012. Retrato de un problema: el sector de la vivienda. In *Un Espacio Para El Desarrollo. Los Mercados de Vivienda En América Latina y El Caribe*, ed. by César Patricio Bouillon, 385. 1st ed. Washington, D.C.: Banco Interamericano de Desarrollo. https://publications.iadb.org/bitstream/handle/11319/3472/Un espacio para el desarrollo%3A los mercados de vivenda en America Latina y el Caribe.pdf;jsessionid=A001F6338E7A60F729EB6F7E79B4A43E?sequence=1.

Brattebø, H., H. Bergsdal, N.H. Sandberg, J. Hammervold, and D.B. Müller. 2009. Exploring built environment stock metabolism and sustainability by systems analysis approaches. *Building Research & Information* 37(5–6): 569–582. http://www.tandfonline.com/doi/abs/10.1080/09613210903186901.

Brunner, P.H. and H. Rechberger. 2005. *Practical Handbook of Material Flow Analysis*. Elsevier. http://thecitywasteproject.files.wordpress.com/2013/03/practical_handbook-of-material-flow-analysis.pdf.

Cordell, D., J.-O. Drangert, and S. White. 2009. The story of phosphorus: Global food security and food for thought. *Global Environmental Change* 19(2): 292–305. http://www.sciencedirect.com/science/article/pii/S095937800800099X.

Costanza, R., B. Fisher, S. Ali, C. Beer, L. Bond, R. Boumans, N.L. Danigelis, et al. 2007. Quality of life: An approach integrating opportunities, human needs, and subjective well-being.

Ecological Economics 61(2–3): 267–276. http://linkinghub.elsevier.com/retrieve/pii/S0921800906000966.

DANE. 2005. CENSO GENERAL 2005. *Población y Demografía*. http://www.dane.gov.co/index.php/poblacion-y-registros-vitales/censos/censo-2005. Accessed June 20, 2002.

Ehrenfeld, J.R. 2000. Industrial Ecology. *American Behavioral Scientist* 44(2): 229–244. http://abs.sagepub.com/content/44/2/229.short. Accessed December 27, 2014.

Erkman, S. 1997. Industrial ecology: An historical view. *Journal of Cleaner Production* 5(1–2): 1–10. http://linkinghub.elsevier.com/retrieve/pii/S0959652697000036.

European Commission. 2011. Communication from the Comission to The European Parliament, The Council, The European Economic and Social Committee and The Committee of The Regions: A Roadmap for moving to a competitive low carbon economy in 2050 - COM(2011) 112. Brussels: European Commission. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0112:FIN:EN:PDF.

European Parliament and The Council of The European Union. 2010. Directive 2010/31/EU on the Energy Performance of Buildings (recast). *Official Journal of the European Union* 53(L153): 13–35. http://eur-lex.europa.eu/legal-content/EN/ALL/;ELX_SESSIONID=0hn8JCTfvhF7jRJyMkmJlzTMXJCl26sxqljHWhQLpjbSyfrygkL2!1996567712?uri=CELEX:32010L0031.

European Parliament and The Council of The European Union. 2012. Directive 2012/27/EU on Energy Efficiency. *Official Journal of the European Union* 55(November): 1–56. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:315:0001:0056:en:PDF.

FAO. 2011. *Global food losses and food waste - Extent, causes and prevention*. Rome. http://www.fao.org/docrep/014/mb060e/mb060e00.pdf.

FAO, IFAD, and WFP. 2015. *The State of Food Insecurity in the World: Meeting the 2015 international hunger targets: taking stock of uneven progress. FAO, IFAD and WFP*. http://www.fao.org/3/a4ef2d16-70a7-460a-a9ac-2a65a533269a/i4646e.pdf.

Fischer-Kowalski, M. 1998. Society’s Metabolism: The Intellectual History of Material Flow Analysis, Part 1, 1860-1970. *Journal of Industrial Ecology* 2(I): 61–78. http://doi.wiley.com/10.1162/jiec.1998.2.1.61.

Fischer-Kowalski, M. and H. Haberl. 1998. Sustainable development: socio-economic metabolism and colonization of nature. *International Social Science Journal* 50(158): 573–587. http://dx.doi.org/10.1111/1468-2451.00169.

Fischer-Kowalski, M. and W. Hüttler. 1998. Society’s Metabolism: The Intellectual History of

Material Flow Analysis, Part 2, 1860-1970. *Journal of Industrial Ecology* 2(4): 107–136. http://doi.wiley.com/10.1162/jiec.1998.2.4.107.

Fischer-Kowalski, M., F. Krausmann, and I. Pallua. 2014. A sociometabolic reading of the Anthropocene: Modes of subsistence, population size and human impact on Earth. *The Anthropocene Review* 1(1): 8–33. http://anr.sagepub.com/content/1/1/8.abstract. Accessed September 29, 2014.

Fischer-Kowalski, M., M. Swilling, E.U. von Weizsäcker, Y. Ren, Y. Moriguchi, W. Crane, F. Krausmann, et al. 2011. *UNEP (2011) Decoupling natural resource use and environmental impacts from economic growth, A Report of the Working Group on Decoupling to the International Resource Panel*. United Nations Environment Programme.

Foley, J. a, R. Defries, G.P. Asner, C. Barford, G. Bonan, S.R. Carpenter, F.S. Chapin, et al. 2005. Global consequences of land use. *Science (New York, N.Y.)* 309(5734): 570–4. http://www.ncbi.nlm.nih.gov/pubmed/16040698.

Gerland, P., a. E. Raftery, H. Ev Ikova, N. Li, D. Gu, T. Spoorenberg, L. Alkema, et al. 2014. World population stabilization unlikely this century. *Science* 346(6206): 234–237.

Gilbert, A.G. 2014. Free housing for the poor: An effective way to address poverty? *Habitat International* 41: 253–261. http://linkinghub.elsevier.com/retrieve/pii/S0197397513000933. Accessed August 30, 2016.

Gordon, R.B., M. Bertram, and T.E. Graedel. 2006. Metal stocks and sustainability. *Proceedings of the National Academy of Sciences of the United States of America* 103(5): 1209–1214.

Gruber, N. and J.N. Galloway. 2008. An Earth-system perspective of the global nitrogen cycle. *Nature* 451(7176): 293–296. http://www.nature.com/doifinder/10.1038/nature06592.

Haas, W., F. Krausmann, D. Wiedenhofer, and M. Heinz. 2015. How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005. *Journal of Industrial Ecology* 19(5): 765–777. http://doi.wiley.com/10.1111/jiec.12244.

Hartmann, M. 2009. *Demographic Methods for the Statistical Office*. http://www.scb.se/statistik/_publikationer/ov9999_2009a01_br_x103br0902.pdf.

Hendriks, C., R. Obernosterer, D. Müller, S. Kytzia, P. Baccini, and P.H. Brunner. 2000. Material Flow Analysis: A tool to support environmental policy decision making. Case-studies on the city of Vienna and the Swiss lowlands. *Local Environment* 5(3): 311–328. http://www.tandfonline.com/doi/abs/10.1080/13549830050134257. Accessed November 18, 2013.

Hertwich, E.G. and G.P. Peters. 2009. Carbon Footprint of Nations: A Global, Trade-Linked

Analysis. *Environmental Science & Technology* 43(16): 6414–6420. http://dx.doi.org/10.1021/es803496a.

Hiç, C., P. Pradhan, D. Rybski, and J.P. Kropp. 2016. Food Surplus and Its Climate Burdens. *Environmental Science & Technology* 50(8): 4269–4277. http://pubs.acs.org/doi/10.1021/acs.est.5b05088.

Hoekstra, A.Y. and T.O. Wiedmann. 2014. Humanity's unsustainable environmental footprint. *Science* 344(6188): 1114–1117. http://www.sciencemag.org/cgi/doi/10.1126/science.1248365.

Hu, M., H. Bergsdal, E. van der Voet, G. Huppes, and D.B. Müller. 2010a. Dynamics of urban and rural housing stocks in China. *Building Research & Information* 38(3): 301–317. http://dx.doi.org/10.1080/09613211003729988.

Hu, M., S. Pauliuk, T. Wang, G. Huppes, E. van der Voet, and D.B. Müller. 2010b. Iron and steel in Chinese residential buildings: A dynamic analysis. *Resources, Conservation and Recycling* 54(9): 591–600. http://www.sciencedirect.com/science/article/pii/S0921344909002407. Accessed September 22, 2014.

IPCC. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)].* Geneva, Switzerland.

Jackson, T. 2009. *Prosperity without Growth? – The transition to a sustainable economy*. https://research-repository.st-andrews.ac.uk/bitstream/handle/10023/2163/sdc-2009-pwg.pdf?sequence=1.

Jahan, S. 2016. *Human Development Report 2016: Human Development for Everyone*. *United Nations Development Programme*. New York, NY.

Kennedy, C.A., I. Stewart, A. Facchini, I. Cersosimo, R. Mele, B. Chen, M. Uda, et al. 2015. Energy and material flows of megacities. *Pnas* 112(19): 1504315112-. http://www.pnas.org/content/early/2015/04/22/1504315112.abstract.

Krausmann, F., M. Fischer-Kowalski, H. Schandl, and N. Eisenmenger. 2008. The Global Sociometabolic Transition. *Journal of Industrial Ecology* 12(5–6): 637–656. http://dx.doi.org/10.1111/j.1530-9290.2008.00065.x.

Land, K.C., Y. Yang, and Y. Zeng. 2005. Mathematical Demography. In *Handbook of Population*, ed. by D.L. Poston and M. Micklin, 659–717. New York: Kluwer Academic Publishers-Plenum Publishers. http://link.springer.com/10.1007/0-387-23106-4_23.

Lee, R.D. and A. Mason. 2011. *Population aging and the generational economy: A global perspective*. Cheltenham: Edward Elgar Publishing.

Liu, G. and D.B. Müller. 2013. Centennial Evolution of Aluminum In-Use Stocks on Our

Aluminized Planet. *Environmental Science & Technology* 47(9): 4882–4888. http://dx.doi.org/10.1021/es305108p.

Lucon, O., D. Ürge-Vorsatz, A. Zain Ahmed, H. Akbari, P. Bertoldi, L.F. Cabeza, N. Eyre, et al. 2014. Buildings. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. by O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, et al. Cambridge, UK and New York, USA: Cambridge University Press. http://report.mitigation2014.org/drafts/final-draft-postplenary/ipcc_wg3_ar5_final-draft_postplenary_chapter9.pdf.

Lunenfeld, B. 2008. An Aging World--demographics and challenges. *Gynecological Endocrinology : The Official Journal of the International Society of Gynecological Endocrinology* 24(1): 1–3. http://www.scopus.com/inward/record.url?eid=2-s2.0-38549116065&partnerID=tZOtx3y1. Accessed August 28, 2014.

Lutz, W. 2012. Demographic Metabolism: A theory of Socioeconomic Change with Predictive Power. *Population & Development Review* 38: 283–301.

Lutz, W., W.P. Butz, and K.C. Samir. 2014a. *World population and human capital in the twenty-first century*. Oxford University Press.

Lutz, W. and R. Muttarak. 2017. Forecasting societies' adaptive capacities through a demographic metabolism model. *Nature Climate Change* 7(3): 177–184.

Lutz, W., R. Muttarak, and E. Striessnig. 2014b. Universal education is key to enhanced climate adaptation. *Science* 346(6213): 1061–1062. http://www.sciencemag.org/cgi/doi/10.1126/science.1257975.

Lutz, W., W.C. Sanderson, and S. Scherbov. 2008. The coming acceleration of global population ageing. *Nature* 451(7179): 716–719.

Max-Neef, M. a., A. Elizalde, and M. Hopenhayn. 1991. *Human Scale Development: Conception, Application and Further Reflections*. Apex Press. http://www.wtf.tw/ref/max-neef.pdf.

Max Planck Institute for Demographic Research. 2018. What is Demography? https://www.demogr.mpg.de/en/education_career/what_is_demography_1908/default.htm. Accessed April 7, 2018.

Meadows, D. 1998. *Indicators and information systems for sustainable development. A Report to the Balaton Group*. https://www.iisd.org/pdf/s_ind_2.pdf%5Cnhttp://www.biomimicryguild.com/alumni/documents/download/Indicators_and_information_systems_for_sustainable_develoment.pdf.

Müller, D.B. 2006. Stock dynamics for forecasting material flows—Case study for housing in The

Netherlands. *Ecological Economics* 59(1): 142–156. http://www.sciencedirect.com/science/article/pii/S092180090500460X. Accessed August 28, 2014.

Murray, C. and D. Clapham. 2015. Housing policies in Latin America: overview of the four largest economies. *International Journal of Housing Policy* 15(3): 347–364. http://www.tandfonline.com/doi/full/10.1080/14616718.2015.1055090.

NCD Risk Factor Collaboration. 2016. Trends in adult body-mass index in 200 countries from 1975 to 2014: a pooled analysis of 1698 population-based measurement studies with 19·2 million participants. *The Lancet* 387(10026): 1377–1396. http://www.sciencedirect.com/science/article/pii/S014067361630054X.

NCD Risk Factor Collaboration (NCD-RisC). 2016. A century of trends in adult human height. *ELife* 5: 1–29. http://elifesciences.org/lookup/doi/10.7554/eLife.13410.

Olaya, Y., F. Vásquez, and D.B. Müller. 2017. Dwelling stock dynamics for addressing housing deficit. *Resources, Conservation and Recycling* 123: 187–199. http://dx.doi.org/10.1016/j.resconrec.2016.09.028.

Pauliuk, S., N.M.A. Dhaniati, and D.B. Müller. 2011. Reconciling Sectoral Abatement Strategies with Global Climate Targets: The Case of the Chinese Passenger Vehicle Fleet. *Environmental Science & Technology* 46(1): 140–147. http://dx.doi.org/10.1021/es201799k.

Pauliuk, S., K. Sjöstrand, and D.B. Müller. 2013. Transforming the Norwegian Dwelling Stock to Reach the 2 Degrees Celsius Climate Target. *Journal of Industrial Ecology* 17(4): 542–554. http://dx.doi.org/10.1111/j.1530-9290.2012.00571.x.

Rayfuse, R. and N. Weisfelt. 2012. *The Challenge of Food Security*. *Science*. Vol. 327. Edward Elgar Publishing. http://www.elgaronline.com/view/9780857939371.xml.

Rockstrom, J., W. Steffen, K. Noone, A. Persson, F.S. Chapin, E.F. Lambin, T.M. Lenton, et al. 2009. A safe operating space for humanity. *Nature* 461(7263): 472–475. http://www.nature.com/nature/journal/v461/n7263/full/461472a.html.

Sandberg, N.H., H. Bergsdal, and H. Brattebø. 2011. Historical energy analysis of the Norwegian dwelling stock. *Building Research & Information* 39(1): 1–15. http://dx.doi.org/10.1080/09613218.2010.528186.

Sandberg, N.H. and H. Brattebø. 2012. Analysis of energy and carbon flows in the future Norwegian dwelling stock. *Building Research & Information* 40(2): 123–139.

Sandberg, N.H., I. Sartori, and H. Brattebø. 2014. Using a dynamic segmented model to examine future renovation activities in the Norwegian dwelling stock. *Energy and Buildings* 82: 287–295. http://www.scopus.com/inward/record.url?eid=2-s2.0-

84905442475&partnerID=40&md5=f0ec5e7d951f4ed7f6402c174f57844d. Accessed September 22, 2014.

Sandberg, N.H., I. Sartori, M.I. Vestrum, and H. Bratteb?? 2016. Explaining the historical energy use in dwelling stocks with a segmented dynamic model: Case study of Norway 1960???2015. *Energy and Buildings* 132: 141–153. http://dx.doi.org/10.1016/j.enbuild.2016.05.099.

Schoenbach, V.J. 2007. Studying populations – basic demography: Some basic concepts and techniques from demography - population growth , population characteristics , measures of mortality and fertility , life tables , cohort effects. In *Understanding the Fundamentals of Epidemiology — an Evolving Text*, 31–52. 4th ed. Chapel Hill, North Carolina: Department of Epidemiology, University of North Carolina, School of Public Health. http://www.epidemiolog.net/evolving/DemographyBasics.pdf.

Seppelt, R., A.M. Manceur, J. Liu, E.P. Fenichel, and S. Klotz. 2014. Synchronized peak-rate years of global resources use. *Ecology and Society* 19(4): art50. http://dx.doi.org/10.5751/ES-07039-190450.

Shafiee-Jood, M. and X. Cai. 2016. Reducing Food Loss and Waste to Enhance Food Security and Environmental Sustainability. *Environmental Science and Technology* 50(16): 8432–8443.

Smith, D.P. and N. Keyfitz. 2013. *Mathematical Demography*. Ed. by Kenneth W. Wachter and Hervé Le Bras. Demographic Research Monographs. Berlin, Heidelberg: Springer Berlin Heidelberg. http://link.springer.com/10.1007/978-3-642-35858-6.

Tilman, D., C. Balzer, J. Hill, and B. Befort. 2011. Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences* 108(50): 20260–20264.

UN-Habitat. 2003. *THE CHALLENGE OF SLUMS: Global Report on Human Settlements 2003.* 1st ed. Nairobi, Kenia: United Nations Human Settlements Programme (UN-Habitat). http://unhabitat.org/books/the-challenge-of-slums-global-report-on-human-settlements-2003/.

UN-Habitat. 2012. *Prosperity of Cities: State of the World's Cities 2012/2013*. *State of the World's Cities*. http://unhabitat.org/books/prosperity-of-cities-state-of-the-worlds-cities-20122013/.

UN-Habitat. 2016. *World Cities Report 2016: Urbanization and Development: Emergin Futures*.

UN. 1956. *Manuals on methods for estimating population - Manual III: Methods for Population Projections by Sex and Age*. *Population Studies*. New York. http://www.un.org/esa/population/techcoop/PopProj/manual3/manual3.html.

UN General Assembly. 2015. Transforming our world: the 2030 Agenda for Sustainable Development. New York: United Nations.

UN, U.N.D. for E. and S.I. and P.A.C. for H.S. and U.N.D. for E. and S.I. and P.A.C. for H.S. UN.

1995. *Compendium of human settlements statistics 1995*. Ed. by Statistics Division and Habitat. Fifth. New York. http://unstats.un.org/unsd/demographic/sconcerns/housing/publications/Series_N5.pdf.

United Nations, Department of Economic and Social Affairs, P.D. 2015. World Population Prospects: The 2015 Revision, DVD Edition. https://esa.un.org/unpd/wpp/Download/Standard/Population/.

United Nations, Department of Economic and Social Affairs, P.D. 2017. World Population Prospects The 2017 Revision Key Findings and Advance Tables. *World Population Prospects The 2017*: 1–46. https://esa.un.org/unpd/wpp/Publications/Files/WPP2017_KeyFindings.pdf.

United Nations Department of Economic and Social Affairs. 1974. *Compendium of housing statistics 1971*. First. New York. http://unstats.un.org/unsd/demographic/sconcerns/housing/publications/Series_N1.pdf.

United Nations Department of Economic and Social Affairs. 1976. *Compendium of housing statistics 1972-74*. Second. New York. http://unstats.un.org/unsd/demographic/sconcerns/housing/publications/Series_N2.pdf.

United Nations Department of Economic and Social Affairs and United Nations Centre for Human Settlements. 2001. *Compendium of human settlements statistics 2001*. Ed. by Statistics Division and Habitat. Sixth. New York. http://unstats.un.org/unsd/demographic/sconcerns/housing/publications/Series_N6.pdf.

United Nations Department of International Economic and Social Affairs. 1980. *Compendium of housing statistics 1975-1977*. Ed. by Statistical Office. Third. New York. http://unstats.un.org/unsd/demographic/sconcerns/housing/publications/Series_N3.pdf.

United Nations Department of International Economic and Social Affairs. 1985. *Compendium of human settlements statistics 1983*. Ed. by Statistical Office. Fourth. New York. http://unstats.un.org/unsd/demographic/sconcerns/housing/publications/Series_N4.pdf.

United Nations University, World Health Organization, and Food and Agriculture Organization of the United Nations. 2001. *Human energy requirements: Report of a Joint FAO/WHO/UNU Expert Consultation*. *FAO Food and Nutrition Technical Report Series*. Vol. 1. Rome, October. http://www.fao.org/docrep/007/y5686e/y5686e08.htm.

UNSD, U.N.S.D. 2015. Slum population as percentage of urban, percentage. *Millenium Development Goals Indicators*. http://mdgs.un.org/unsd/mdg/seriesdetail.aspx?srid=710.

Vásquez, F., A.N. Løvik, N.H. Sandberg, and D.B. Müller. 2016. Dynamic type-cohort-time approach for the analysis of energy reductions strategies in the building stock. *Energy and Buildings* 111: 37–55. http://www.sciencedirect.com/science/article/pii/S0378778815303832.

Vitousek, P.M., H.A. Mooney, J. Lubchenco, and J.M. Melillo. 1997. Human Domination of Earth's Ecosystems. *Science* 277(5325): 494–499. http://www.sciencemag.org/content/277/5325/494.abstract.

Wackernagel, M., N.B. Schulz, D. Deumling, A.C. Linares, M. Jenkins, V. Kapos, C. Monfreda, et al. 2002. Tracking the ecological overshoot of the human economy. *Proceedings of the National Academy of Sciences of the United States of America* 99(14): 9266–71. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=123129&tool=pmcentrez&rendertype=abstract.

Weizsäcker, E.U. von, J.A. De Larderel, K. Charlie, C. Hudson, M.H. Smith, and A.E. Rodrigues. 2014. *UNEP (2014) Decoupling 2: technologies, opportunities and policy options. A Report of the Working Group on Decoupling to the International Resource Panel*.

World Commission on Environment and Development. 1987. *Our Common Future*. http://www.un-documents.net/our-common-future.pdf. Accessed May 3, 2017.

Xue, L., G. Liu, J. Parfitt, X. Liu, E. Van Herpen, A. Stenmarck, C. O'Connor, K. Östergren, and S. Cheng. 2017. Missing food, missing data? A critical review of global food losses and food waste data. *Environmental Science & Technology*: acs.est.7b00401. http://pubs.acs.org/doi/abs/10.1021/acs.est.7b00401.

Paper 1

Dynamic type-cohort-time approach for the analysis of energy reductions strategies in the building stock.

Vásquez, F., A.N. Løvik, N.H. Sandberg, and D.B. Müller. 2016. Energy and Buildings 111: 37–55. http://www.sciencedirect.com/science/article/pii/S0378778815303832.

Energy and Buildings 111 (2016) 37–55

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Dynamic type-cohort-time approach for the analysis of energy reductions strategies in the building stock

Felipe Vásquez*, Amund N. Løvik[1], Nina Holck Sandberg[2], Daniel B. Müller[3]

Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway

ARTICLE INFO

Article history:
Received 6 June 2015
Received in revised form 5 November 2015
Accepted 6 November 2015
Available online 14 November 2015

Keywords:
Type-Cohort-Time TCT
Stock dynamics
Dynamic material flow analysis MFA
Nearly zero energy buildings NZEB
Renovation
Vacancy
Germany
Czech Republic
Residential sector
Building stock

ABSTRACT

While many countries have set ambitious targets for reducing energy use and GHG (greenhouse gas) emissions, it remains highly uncertain whether the policies introduced will be suitable to reach these targets at the specified times. Models used to inform building policies often do not account for the different boundary conditions related to socio-economic development, climate, composition and age structure of the existing building stock, and lifetime expectancy, which hinders effective strategy development and realistic target setting. This study presents a dynamic Type-Cohort-Time (TCT) stock-driven modelling approach that considers demographic aspects, lifestyle-related issues, and building-specific characteristics. Case studies were conducted for the dwelling stocks in Germany and the Czech Republic, two countries with different boundary conditions, but that are sheltered under the same European energy-reduction policies and goals. The effects of the policies on nearly zero energy buildings and increased renovation rates were tested. The results showed that current regulations are sufficient to achieve the 20% energy efficiency goal by 2020, but not to reach the 2050 energy and GHG-emission goals. The scenarios further demonstrate that the same policies on renovation and construction in different countries lead to different energy reduction levels. Accordingly, country-specific policies and measures are suggested.

1. Introduction

The buildings sector is crucial for the reduction of overall energy use and climate change mitigation. According to the IPCC [1,2] the operation of the building stock is currently responsible for almost one third of the final energy demand and around one fifth of the greenhouse gas (GHG) emissions worldwide. Baseline scenarios project a doubling of the energy demand and a rise by 50–150% in CO_2 emissions by mid-century in the sector [1]. If already available cost-effective best practices and technologies are broadly diffused final energy use may stay constant or even decline in the same period [2]. Yet, the achievement of significant energy reductions requires a deep and fast transformation of the building stock [2,3] to a zero or even positive energy system.

In the European context, buildings are considered to have the largest energy-saving potential among all sectors [4]. Thus, the promotion of the aforementioned transformation has been led by the European Directives on the Energy Performance of Buildings (EPDB) and on Energy Efficiency (EED), and the Energy Efficiency Plan 2011 [3,5,6]. These policies have decreed (i) the need for increased renovation rates, (ii) minimum energy performance requirements during major buildings' renovation, and (iii) the implementation of all new buildings after 2020 as NZEB (nearly zero-energy buildings).

Through these policies the building sector is expected to significantly contribute to the achievement of the European goals of saving 20% of the Union's primary energy consumption by 2020 compared to projections [4], and of reducing GHG emissions in the residential sector by 88–91% by 2050 with respect to the emission level of 1990 [7].

Consequently, robust building stock models are essential for informing decision makers about the effectiveness of different policies or combinations of policies for (i) realizing current goals, (ii) defining realistic goals, (iii) prioritizing climate change mitigation strategies, and (iv) avoiding misinformation and fragmented actions and policies that lead to weaker results in the long run [8]. The IPCC's fifth assessment report already identified a lack of adequate models in this regard [2,9]. Currently, LCA (life cycle

---

* Corresponding author. Tel.: +47 46448020.
E-mail addresses: luis.v.correa@ntnu.no (F. Vásquez), amund.lovik@ntnu.no (A.N. Løvik), nina.h.sandberg@ntnu.no (N.H. Sandberg), daniel.mueller@ntnu.no (D.B. Müller).
[1] Tel: +41 796679874.
[2] Tel: +47 45280475.
[3] Tel: +47 91897755.

http://dx.doi.org/10.1016/j.enbuild.2015.11.018
0378-7788/

assessment), economic input-output LCA, and hybrid LCA are the most widely used approaches for supporting decisions for individual buildings [10]. Nonetheless, these are insufficient to address the gap between targets and expected outcome from policies on national or regional levels.

Models of the energy use of the building stock have to be able to handle the complex and heterogeneous nature of the stock [11,12]. This complexity can be dealt with by decomposing the stock into its essential dimensions. Consequently, models can be characterised by the different dimensions they incorporate along with their driving forces and modelling techniques. Three dimensions are emphasized: (i) building types, (ii) cohorts, and (iii) time. The types and cohorts correspond to the way the building stock is structured (typology). Combinations of these two are commonly described in the literature as archetypes. Both dimensions are important because they are representative of the buildings' construction technology/materials and energy performance. Time refers to the modelling time frame – one or several years – and whether this corresponds to historic, present, or future situation. Models addressing long time periods are of high importance to capture inertia and lock-in effects related to the long lifetime of buildings. Differentiated lifetime across building cohorts and types complements the archetypes.

The model's driving forces and modelling techniques are interrelated. We refer to these as modelling approaches or types of models. These can be classified into three: (i) accounting, (ii) quasi-stationary, and (iii) dynamic. Dynamic models are further divided into (a) input-driven or activity-driven, and (b) stock-driven. Accounting models mainly quantify the stock size and composition, and associated material or energy flows. This type of model is based on reckoning principles and does not intend to analyse the drivers of the stock development and energy use. In contrast, the other two model approaches make use of different drivers to explain the size, composition, and energy consumption of the stock. Quasi-stationary models commonly study the building stock for one single year, while dynamic models analyse multiple years. The activity-driven models generally use construction and demolition rates, mostly based on historic trends, as drivers. The stock-driven models use the service demand/provision concept [13], which relies on time-changing factors like population and preference in size and type of building. Stock-driven models use the buildings' lifetime for explaining and estimating construction and demolition activities. In turn, this type of model requires a longer modelling time-span due to the long lifetime of buildings. The impact of renovation is often captured by the use of renovation rates or renovation cycles.

Table 1 presents a review of existing models and studies for the energy use in the building stock using the discussed classification of dimensions and model approaches. The further to the right and to the bottom a model is positioned in Table 1, the greater its analytical capabilities and the larger the input data requirements. This is more characteristic of bottom-up models since top-down models are normally "accounting models" and commonly aggregate the stock into one type and one cohort. Studies addressing only one type and/or one cohort and/or one year are useful to identify key challenges of specific parts of the stock, but are unsuitable to address long-term challenges and to inform policies and targets of the sector. Most of the current studies concerned with multiple types and multiple cohorts lie within the accounting or activity-driven modelling approaches. The majority of these studies focus on the existing stock while disregarding the role of future buildings.

The presented references either mention the name of the author, the institution, the model, or the project. The "one type" classification refers either to studies addressing one specific type of building or the building stock as a whole (i.e. no type differentiation). One cohort refers to studies analysing buildings built in a specific year or range of years (because similarities in construction technology), or to studies on the total building stock without cohort differentiation. Some of the presented studies could be classified differently because they have components that may lie between two or more modelling approaches. Some studies use the type dimension for the differentiation of household, appliances/technologies, or energy-carriers types instead of building types.

There is a gap of studies that: (i) use stock-driven models; (ii) are multi-type, multi-cohort and multi-year in the approach; and, (iii) evaluate the energy demand of not only the existing but also the future buildings. Only one study, carried out by Pauliuk et al. [63], was found to be positioned at this methodological level. Although there are a growing number of studies of the building stock using multidimensional stock-driven models, these have focused on topics other than energy. Most of them are concerned with stock development (stock size, stock change, construction and demolition) and/or materials [13,64–70].

Here, we present a *dynamic stock-driven type-cohort-time* (TCT) approach based on MFA principles that aims to fill this research gap. Two case studies on the residential building stocks of Germany and the Czech Republic were developed. The effects of a successful implementation of the European policies on NZEB by 2020 and increased renovation rates were tested and compared with national and European energy targets. The TCT approach was also used to identify priority areas for mitigation actions in different specific parts of the stocks.

The choice of the countries was based on: (i) the past and expected future socio-economic differences between them; (ii) the data availability for the composition and energy performance of the existing stock; and, (iii) the relevance of the dwellings in the national buildings stock and energy consumption.

2. Method

2.1. System definition

The system describes floor-area development and energy use of the dwelling stock (see Fig. 1). The dwelling stock was differentiated using the types and cohort groups reported by the European projects TABULA and EPISCOPE [26], in accordance to the "European unified building typology". Single-Family Houses (SFH), Terraced Houses (TH), Multi-Family Houses (MFH), and Apartment Blocks (AB) were the four dwelling types studied.

Living area, according to national definitions, was the used reference floor-area. Energy use includes the theoretical delivered energy for space heating and hot water during the dwellings' use phase. The energy definition follows the EN ISO 13790 standard [71], and excludes energy for appliances. Issues related to primary and final energy, losses in transmission, energy carriers, user-related energy consumption behaviour, and GHG emissions are beyond the scope of the study.

2.2. Model description

A dynamic stock-driven model (see Fig. 1) was developed for tracking flows of floor area and energy through all type-cohort fractions of the stock. Floor-area stocks and flows were studied for the period 1800–2100. Energy was studied for the period 2010–2100. The 301-years modelling time frame allotted sufficient time-step calculations to account for the stock's slow change in composition due to the long lifetime of buildings. The last year, 2100, corresponds to the current last year in the climate change discourse [1].

The model builds on Müller's [13] dynamic MFA-model and following applications. Six different output variables are generated:

Table 1
Models and studies for energy use in the building stock: classification by modelling dimensions and approaches according to MFA (material flow analysis).

Time	Type		One type		Multiple type	
	Model approach		Cohorts			
			One cohort	Multiple cohorts	One cohort	Multiple cohorts
One Year	Accounting		Amstalden et al. [14]	Salat [15]	Aydinalp and Ugursal [16] Shimoda et al. [17] Cuerda et al. [18]	Parekh [19] Huang and Brodrick [20] Jones et al. [21] Swan et al. [22] Nemry et al. [23] Tornberg and Thuvander [24] Snäkin [25] TABULA/EPISCOPE [26] Dascalaki et al. [27]
	Quasi-Stationary		Larsen and Nesbakken [28] Hong et al. [29]		Capasso et al. [30] Choudhary [31]	Aydinalp et al. [32] Swan et al. [33] Dall'O' et al. [34]
Multiple Years	Accounting		Haas and Schipper [35] Bentzen and Engsted [36] Emery and Kippenhan [37] Kadian et al. [38] Sartori et al. [39]		Nesbakken [40] Tommerup and Svendsen, [41]	CREEM [42] Itard and Meijer [43]
	Dynamic	Activity Driven	Ozturk et al. [44] Buildings Performance Institute Europe [45]		LC-Build [46] Onat et al. [47]	Kohler et al. [48] Palmer et al. [49] BEAM [50] NEMS [51] Siller et al. [52] Hens et al. [53] DEE-Czech [54] McKenna et al. [55] Bettgenhäuser [56,57] Boermans et al. [58] Reyna and Chester [59]
		Stock Driven	Sandberg et al. [60] Sandberg and Brattebø [61]	Müller et al. [62]		Pauliuk et al. [63]

Stock (S), Stock Change (ΔS), Construction (I), Demolition (O), Stock Vacancy (λ), and Energy Use (E). All variables are studied in three dimensions: by Type of dwelling (j), by Cohort (c), and in Time (t) on a yearly basis, TCT. Each cohort corresponds to only one specific year. A cohort-group corresponds to a period of several years where dwellings share similarities in technology and materials, and therefore perform similarly energy-wise.

The stock dynamics and the subsequent energy demand are driven by six parameters: Population (P), Floor Area per Capita (FApC), Type Split of Construction (TS), Mean Lifetime of Dwellings (τ), Lifetime Standard Deviation (σ), and Energy Intensity of the Dwellings (ε). FApC and TS are representative of the lifestyle of a given period. τ, σ and ε are representative of the buildings' technology.

A detailed model description is presented in Appendix A (see Appendix A1). The stock (S) is found by multiplying the population (P) and the dwelling service level (FApC). The composition of the stock at a given year is defined by (i) the size and type split of the construction activity of that year (see Eq. (1)), and by (ii) the size and type split of the still-standing dwellings of each one of all the previous cohorts. The standing stock of a specific cohort in a given year is explained by the cohort's initial size when constructed minus its accumulated demolition until that year.

The total construction of a year is the sum of (i) the net addition to stock (ΔS)—which responds to the change in population and lifestyle standards and (ii) the substitution of the dwellings reaching the end of their service life (O). The construction of a specific type of dwelling is defined by the type split-share ($\mathrm{TS}_{j,c}$) as in the following equation:

$$I_{j,t} = (\Delta S_t + O_t) \cdot \mathrm{TS}_{j,c} \tag{1}$$

The demolition of a type-cohort combination in a specific year (see Eq. (2)) is a function of (i) its size at construction ($I_{j,c}$), and (ii) its probability of reaching the end-of-service-life ($f_{j,c,t}$) given its age. $f_{j,c,t}$ is derived from the probability density function of a normally distributed lifetime.

$$O_{j,c,t} = I_{j,c} \cdot f_{j,c,t} \tag{2}$$

The total energy demand (see Eq. (3)) in a given year is the sum of the individual energy intensities ($\varepsilon_{j,c,t}$) of the different parts (type-cohort combinations or segments) of the in-use stock ($S_{j,c,t}$). The in-use stock is the total stock adjusted for vacancy (λ).

$$E_t = \sum_{j} \sum_{c=1}^{t} \varepsilon_{j,c,t} \cdot S_{j,c,t} \cdot (1 - \lambda_t) \tag{3}$$

The energy intensities of the different type-cohort segments progressively decrease in time, unless the contrary is specified. These energy gains indirectly represent renovation since this activity is not explicitly modelled. Specifics on energy intensities and renovation are further explained in the following subsections and Appendices A4 and A5.

Vacancy represents floor-area surplus. It occurs when the standing stock exceeds at meeting the service needs, which also signifies

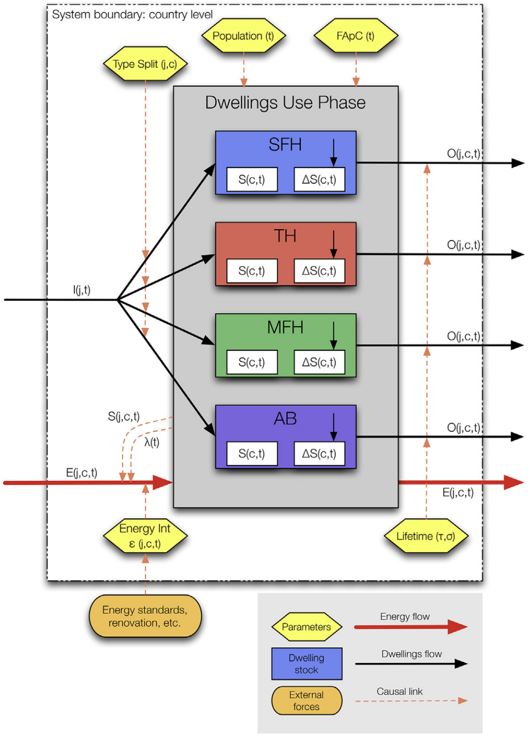


Fig. 1. System and model definition. Variables: *S*—Stock, Δ*S*—Stock Change, *I*—Construction, *O*—Demolition, λ—Vacancy, *E*—Energy Demand. Parameters: *P*—Population, FApC—Floor Area per Capita, TS—Type Split, τ—Average Lifetime, σ—Lifetime Standard Deviation. Dimensions j-type, *c*—cohort, *t*—time. Dimensions: SFH—Single Family House, TH—Terraced Houses, MFH—Multi-Family Houses, AB—Apartment Blocks.

no need for new construction. Vacancy is characteristic of steady or declining population and/or living standards, and it is a new concept in dynamic MFA modelling. This concept of vacancy differs form the traditional definition, which is mainly a market-based indicator. Our model does not account for the market vacancy because the FApC values were derived from statistics reporting only on occupied dwellings.

2.3. *Parameter estimation*

Fig. 2 illustrates the long-term development in the input parameters *P*, FApC, TS, τ and σ. The input values for ε are independently presented in Fig. 3. Population and Floor Area per Capita were described by using a logistic function and by applying a non-linear regression method on the available statistics (see Parameters Values Used in Fig. 2).

Population (P) numbers, historical and projections, were mainly based on information from the statistical offices of the respective countries [72–77]. Assumptions about the future population were based on medium projection scenarios.

Data for *Floor Area per Capita (FApC)* was obtained from diverse statistical sources [77–82]. Historical data prior to 1950 were sparse. An initial value of 10 m^2/cap in 1800 was assumed for both countries based on early assumptions by Bergsdal et al. [66] for Norway. An end stabilisation value of 48 m^2/cap in 2100 for Germany and in 2140 for Czech Republic was assumed. The 40-year lag between countries was defined under the premise that today's values in Czech Republic were reached by Germany approximately 40 years ago; and it is expected that Czech Republic develops and industrialises in a similar way as Germany did it in the past. The assumption for the stabilisation level is conservative, particularly for Germany where it implies little growth from today's level of 43 m^2/cap. The choice is however supported by the German trends in the constituent factors of FApC – Floor Area per Dwelling (FApD) and People per Dwelling (PpD), where FApC = FApD/PpD – over the last three decades [80,81,83–91] (see Figs. A1 and A2). In this period, FApD grew less than 10 m^2 per dwelling with a trend towards flattening and stabilising around 90 m^2 per dwelling. In addition, the

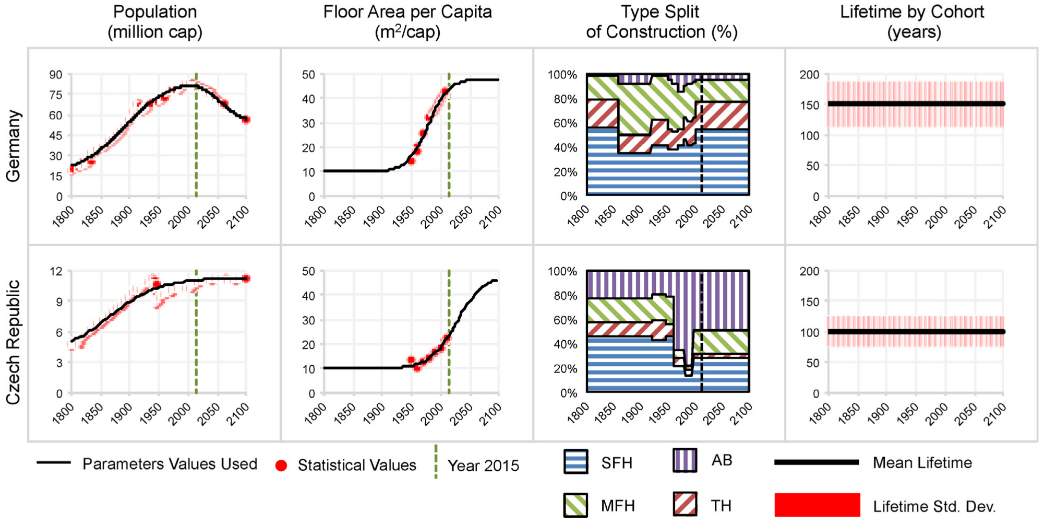


Fig. 2. Model input parameters. Population, floor area per capita, and type split of construction are displayed annually (time in the horizontal axis). Mean lifetime and its standard deviation are presented by cohort (cohorts in the horizontal axis).

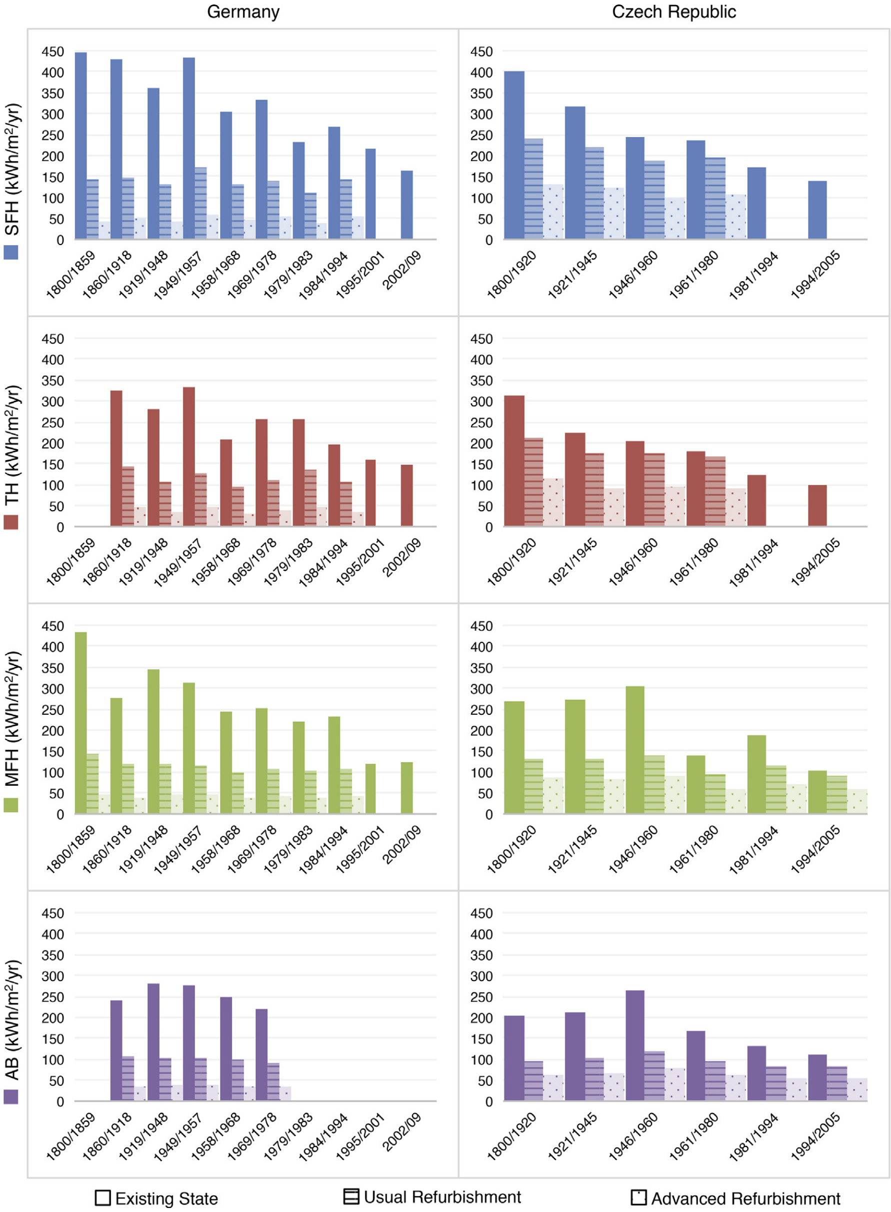


Fig. 3. Energy intensities (ε) for different types and cohorts for existing state (2012), usual refurbishment, and advanced refurbishment: raw data from TABULA [26]. Numbers are based on example buildings and are available for dwellings built until 2009 and 2005 for Germany and Czech Republic, respectively. Numbers are reported for 4 dwelling types, and are available for 10 cohort groups for Germany and 6 cohort groups for Czech Republic for almost all types of dwellings.

numbers of persons per dwelling has shown signs of stabilisation towards 2.0 persons per dwelling.

Data on the *Type Split (TS) of Construction* for the four dwelling types was not found. The annual values were obtained by assuming that the current type-distribution in each cohort [26] corresponds to the type-split when the cohort was built. This implicitly means that all dwelling-types in a cohort (or cohort group) were assumed to have same average lifetime. The split of future cohorts was assumed to remain constant at present values. In reality, TS is characterized by large inter-annual variations due to rapid market demand and dwelling preference fluctuations, which were not studied.

A fixed expected *Lifetime* (τ) for all cohorts in each country was assumed (see Fig. 2). σ was assumed to be 1/4 of τ. Through a process of model calibration and results validation to different lifetimes (see Appendix A3), the German dwelling's average lifetime was estimated to lie around 150 years and the Czech's around 100 years.

Energy Intensity (ε) represents the annual average delivered energy per m^2 of living area ($kW\,h/m^2/yr$). Numbers for the presently exiting dwellings were taken from TABULA [26]. TABULA reports three energy performance levels – (i) existing state, (ii) usual refurbishment, and (iii) advanced refurbishment – for 34 and 24 different type-cohort-group combinations in Germany and Czech Republic, respectively (see Fig. 3). The different energy performance levels were used as input values for forecasting of the present and future yearly energy intensities (energy performance profiles for 2010–2100) of existing dwellings in each scenario, and for indirectly modelling renovation. The energy performance profiles and renovation modelling are further explained in Appendix A4 and Fig. A5. Numbers from TABULA were also used to define the different energy performance-levels' values of the future dwellings in the TRENDS scenario (see Section 2.4 and Appendix A5). For simplicity we have assumed that a NZEB is a dwelling that demands zero energy from the grid (zero delivered energy) during its use phase. More considerations on energy are presented in the following section.

2.4. Scenarios

Four forecasting scenarios – TRENDS, REN, NZEB and RENZEB – concerned only with current European on the energy performance of new and renovated buildings were developed. These were modelled by changing the energy intensity parameter ε in different cohorts and times. Since other parameters are not affected by these policies, they were assumed to remain unchanged to allow comparison.

The *TRENDS Scenario* sets a baseline for analysis and can be regarded as a worst-case scenario. It builds on the premise that the countries fail at the implementation of current policies in the sector (i.e. NZEB and increased renovation rates). Consequently, the technological development follows past trends and renovation rates remain at current levels.

Three technology learning curves were derived for each dwelling type – based on the energy intensities in Fig. 3 (past cohorts) – to establish the energy performance of the future cohorts over time. The first curve defines the energy intensity at year of construction. The two other set the cohort-dependent energy gains at usual and advanced refurbishment levels. More details are presented in Appendix A5.

Since available data on renovation rates are not explicit about the cohorts refurbished, we used instead renovation cycles to model cohort-specific renovation activities. A renovation cycle is defined as the time required for a cohort or cohort group to move from one energy performance level to another (e.g. the cohort's average energy intensity moves either from the existing state to the usual refurbishment, or from the usual refurbishment to the advance refurbishment level). Analogously, we can consider this time as the average time that takes a dwelling to undergone a deep renovation (commonly of facades) [65]. Following this line of reasoning and based on results and discussions presented by other authors [51,52,65,92,93], we associated current renovation rates – around 1% [45,54,55] – to correspond to a renovation cycle of 50 years, which is a common average time for a building to undergone a deep renovation. Subsequently, each cohort was modelled to linearly achieve an average energy intensity equivalent to a new refurbishment level every 50 years. This means that the average usual refurbishment level is achieved in 50 years, and the average advanced refurbishment level in 100 years–50 years after the usual level.

The *REN Scenario* studies the policy for increased renovation rates in isolation. Since the EPBD does not explicitly specify renovation rates, we followed the German approach to the policy of doubling the current rates [94], from 1% to 2% [55]. We tested this policy by means of a halving in the renovation cycle, from 50 to 25 years. Since Czech Republic does not have specific renovation rate targets the same halving approach was used. The energy performance of the future cohorts over time was defined as in the TRENDS scenario but using a halved renovation cycle. The same renovation cycle was applied to all type-cohort segments of the stock.

The *NZEB Scenario* analyses the effects of a successful deployment of the NZEB policy in isolation. Thus, it builds on the premises that (i) by 2020 all new dwellings are built as zero energy demanding, and that (ii) renovation rates stay at the current level as in the TRENDS scenario. We further assumed technology stagnation after the introduction of NZEB. Hence, all dwellings built after 2020 remain at zero level.

The *RENZEB Scenario* explores the case of a successful implementation of both policies on increased renovation rates and NZEB by combining the assumptions of the REN and NZEB scenarios.

3. Results

3.1. Stock dynamics

The German stock is expected to reach a maximum around 2030 and to subsequently shrink during most of the century (see Fig. 4). The stock decline is accompanied by the decline in population during most of the century and a very high average service level already in 2030 (FApC c.a. 46 m^2/cap). In the Czech Republic, the stock will grow for the rest of the century, although this growth slows down during the last three decades. During those three decades the population has almost stopped growing while the FApC has reached 43 m^2/cap (present level in Germany). The growth of the stock by the end of the century will be driven primarily by the growth in service level.

Future construction shows different trends in the two countries, mainly due to the long but different lifetimes (lower part of Fig. 4). During the past two decades Germany has been experiencing a steady decrease in construction activity, which, as predicted by the model, will continue until about 2040. A roughly 40-years period without need for new dwellings follows. The last two decades of the century will be marked by a re-increase in construction in order to compensate for those dwellings reaching the end of their service life. The Czech construction activity in contrast will steadily increase until around 2030 when a slight decrease will take place.

Our model results correspond well with statistics of the historical stock size and construction activity, with the exception of construction activity in Czech Republic. The model validation and uncertainties in the results are discussed in Section 4.4.

3.2. Energy demand

The scenarios' results (see Figs. 5, 6 and 8) are compared with three fictive energy reduction targets – 20% by 2020, and 50% and 80% by 2050 – with respect to the modelled 2010 levels. The target to 2020 can be indirectly associated with the EU goal of 20% energy efficiency by 2020 [4], and with the Czech target to reduce the national final energy consumption by around 20% by 2020 [54]. The 2050 targets correspond roughly to the German goals of reducing primary energy consumption in the country by 50% and in the buildings sector by 80% by 2050 with respect to 2008 levels [105]. While Germany does not have related targets to 2020, Czech Republic does not have them to 2050. The authors consider that energy results after 2050 should be regarded as highly uncertain due to the long

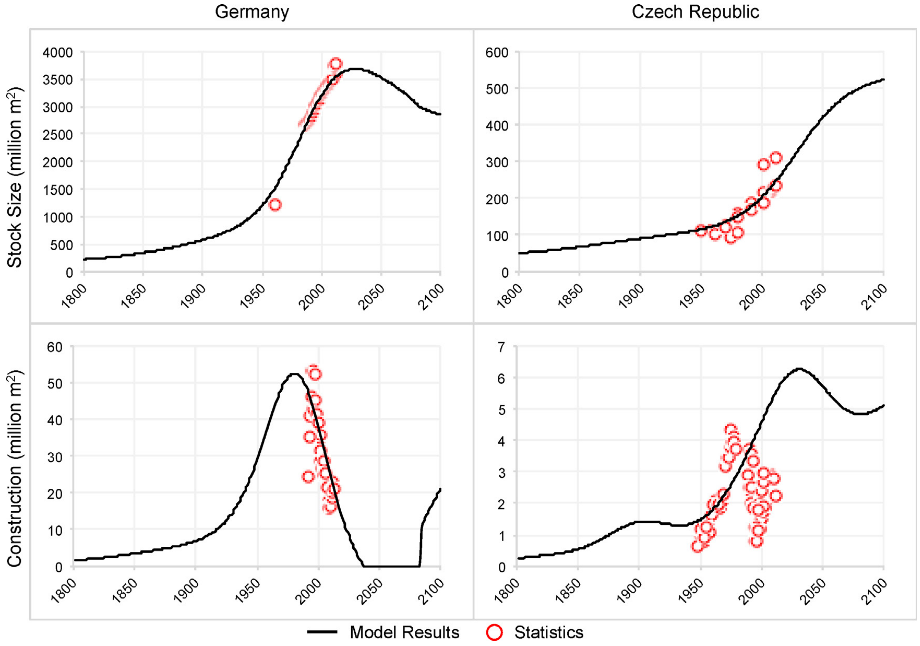


Fig. 4. Stock development (top) and modelled construction (bottom) by country. Results are compared with historic available values from diverse sources [79–87,89,90,95–104].

modelling time frame and the uncertainty that involves the prediction of the technological development for buildings of all types and cohorts, energy mix, population and lifestyle.

While the TRENDS scenario is sufficient for Germany to achieve a 50% energy reduction by 2050, it would not allow the Czech Republic to significantly reduce energy consumption in the same period. In this scenario, cohorts from 1800 to 2014 dominate energy use in Germany; while in the Czech Republic new dwellings (cohorts after 2015) are as important as the existing ones (Fig. 7). For this reason, the implementation of NZEB would allow the Czech Republic to closely converge to an energy reduction of 50% by 2050, while these will not contribute to significant additional energy savings in Germany. In contrast, the REN scenario–renovation measures–generates additional energy reductions in both countries but these are significantly larger in Germany where almost a 75% reduction is reached. Only a full deployment of RENZEB policies allows the Czech Republic to achieve the 50% long-term target (by 2050) and to almost accomplish the 20% short-term target (by 2020). Germany accomplishes the short-term goal under the REN and RENZEB scenarios and the 50% long-term goal under all scenarios. However, even the ambitious policies involved in RENZEB are not sufficient for reaching an 80% reduction by 2050 by any of the countries.

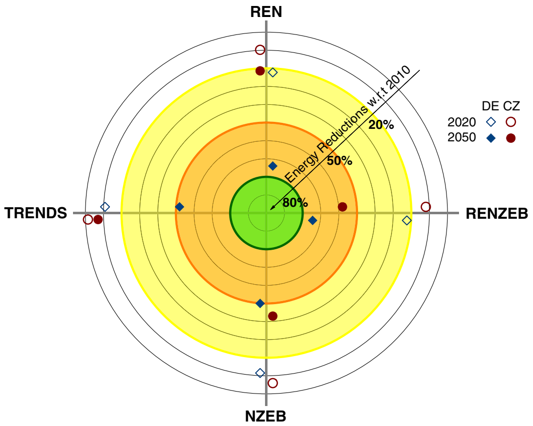


Fig. 5. Delivered energy reductions in 2020 (empty shapes) and 2050 (filled shapes), relative to 2010, by scenario and country (Germany in blue and Czech Republic in red). Each scenario is represented by one half-axis of the target-like diagram, and the concentric rings represent the energy reductions targets of 20% (yellow), 50% (orange), and 80% (green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Although the global results position Germany in a more favourable situation than Czech Republic for the achievement of the energy reduction targets, Germany still demands 2–3 times more energy “per capita” and up to 2 times more energy “per square-meter”, both in the short- and long-terms (Fig. 8). Only through the REN scenario the German stock performs similarly to the Czech in the long-term. Overall, Germany achieves larger relative reductions in total delivered energy across scenarios despite having a more inefficient stock at all times. Alternatively, the Czech Republic achieves larger relative per square-meter energy reductions in most of the cases, but does not achieve its total delivered energy goals (except the 50% in the RENZEB scenario). Germany always attains larger per capita relative reductions than Czech Republic.

Results demonstrate that the NZEB-strategy is effective in countries with high new construction rate like Czech Republic, while the renovation-strategy is effective in countries with large inefficient stocks. In addition, the NZEB-strategy is effective over

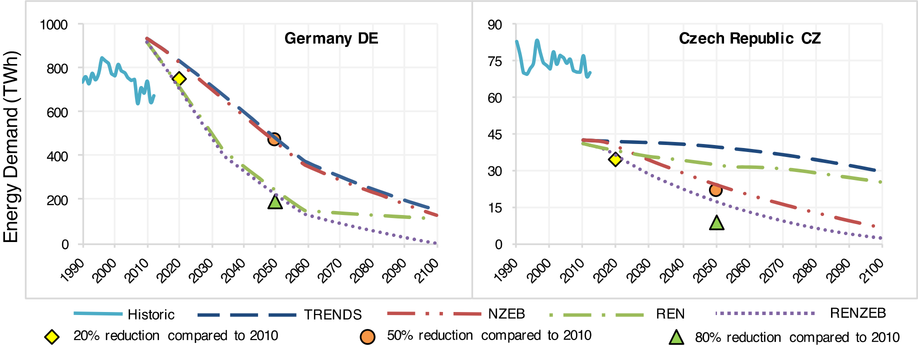


Fig. 6. Scenarios' delivered energy results for space heating and hot water in TW h in the period 2010–2100 in Germany DE (left) and Czech Republic CZ (right). The historic energy use (1990–2010), from Eurostat [106], is reported as final energy and it is therefore not directly comparable to the results but presented as a reference for discussion.

long time period while renovation-strategy shows more immediate effect, which is more relevant for short-term goals.

The identification of priority areas for energy saving requires an understanding of the energy-demand contribution of individual cohorts and dwelling types. Fig. 9 disaggregates this contribution for the period 2015–2050. The cumulative energy demand in Germany from 2015 to 2050 is mainly driven by Single Family Houses (SFH) and Multi-Family Houses (MFH) built between 1919 and 1994. The future energy demand in Czech Republic exhibits a different pattern: it will be greatly pushed by Apartment Blocks (AB) built between 1961 and today, and SFH built after 1994. SFH will be particularly important in Czech Republic if increasing levels of wealth lead to more individualistic lifestyles as observed in Western countries. Fig. 9 also demonstrates how new construction is of limited importance for the energy demand in the German dwelling stock, but plays an important role for the total energy demand in the Czech dwelling stock.

4. Discussion and conclusions

4.1. Country-wise differences in energy demand

Currently, Germany demands around 22 times more energy than the Czech Republic, which can be explained by:

1. The fact that Germany has a stock 13 times larger than Czech Republic (Fig. 4), described by a population and a floor area per capita 7 and 1.9 times larger, respectively (Fig. 2).
2. Overall, buildings – of similar type/cohorts – are more efficient in Czech Republic than in Germany (Fig. 3). This results in a specific energy demand per square meter 1.6 times larger in Germany in 2010 (bottom Fig. 8).
3. The Czech Republic has a much higher share of apartment blocks, which are more energy efficient than the other types common in Germany, especially SFH (see Type Split of Construction in Fig. 2). A table with composition and the relative distribution by types for the stock of both countries in 2010 is presented in Appendix A6.

In the long term this difference in total delivered energy demand between both countries decreases. In the RENZEB scenario, in 2050, Germany demands 13 times more energy with a stock 8 times larger than the Czech.

Because goals are defined with respect to total energy demand rather than with respect to an specific energy demand (i.e. per capita and per square meter), Germany requires less efforts to achieve the 50% goal than Czech Republic. Overall, Germany will have some energy savings without doing anything, just because the stock will be shrinking due to the decrease in population. Czech Republic, on the other hand, will have to reduce the energy demand despite of the increase in population and floor area per capita. Despite having a more inefficient stock, Germany requires reductions of 48% or 43% in energy demand per square meter and per capita, respectively (with respect to 2010), while the reductions required in Czech Republic are of 71% or 50%.

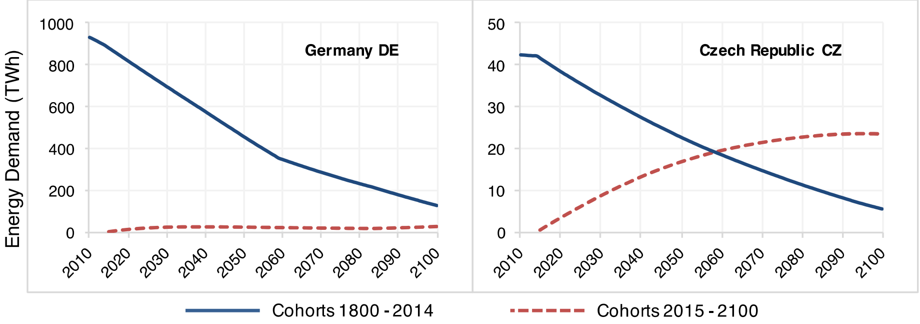


Fig. 7. Energy demand in the TRENDS Scenario (TW h/year)—Cohorts 1800–2014 vs. Cohorts 2015–2100—Germany DE (left) and Czech Republic CZ (right).

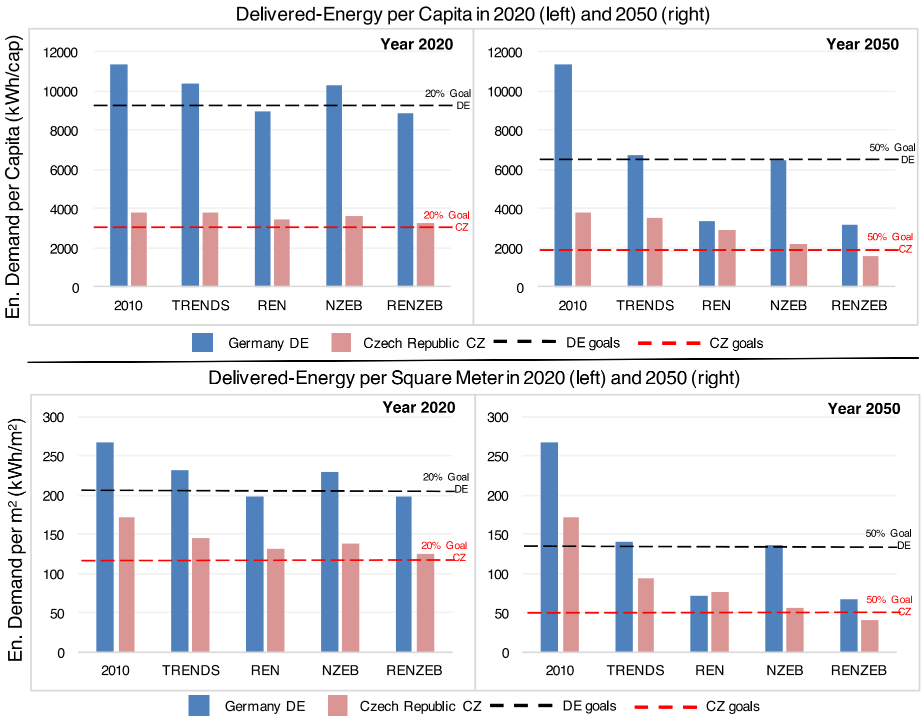


Fig. 8. Delivered energy per capita (top) and per square meter (bottom) in 2020 (left) and 2050 (right) in Germany (blue bars) and Czech Republic (light red bars) by scenario. 2010 values are presented for comparison. The German (black dashed line) and Czech (red dashed line) goals correspond to the absolute energy reduction goals and do not represent per capita or areal goals. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.2. Policy

The results indicate that current policies are sufficient for both countries to reach a 20% energy efficiency gain in the residential buildings by 2020 but not to achieve the GHGs targets of an 80% reduction by 2050 (the latter assuming no decarbonisation of the delivered energy). The sectorial German energy reduction goal of 80% by 2050 is also unattainable with current building policies. The Czech Republic has not set energy goals for 2050. The forecasted energy efficiency gains by means of current policies in 2050 (with respect to 2010) are 75% and 58% for Germany and Czech Republic, respectively. The Global Energy Assessment (GEA) [112] concluded in 2012 that a reduction of nearly 46% of the 2005's global final heating and cooling energy use is possible by 2050 through the proliferation of today's best practices; without sacrificing the increase in lifestyle standards and without interceding in economic and population growth. Our model results agree with GEA's conclusion.

To reach the 2050 climate targets both countries need to take additional measures, either by further reducing energy demand or by decarbonizing the energy delivered.

The case studies demonstrated that the same building energy policies result in very different long-term energy gains in different countries. For example, new construction policies are highly effective in the Czech Republic—36% additional energy gains with respect to trends in 2050, while they have a very small effect in Germany—2% additional energy gain. In turn, renovation policies have a high impact in Germany—25% additional energy gain, but are less crucial in the Czech Republic—15% additional energy gain. The effectiveness of energy policies in the building sector is thus highly dependent on the context of the building stock development, in particular the composition of the existing stock, its growth rate, and the lifetime of its buildings. European regulations require the same ambitious measures for both, renovation and new construction in all member states. This strategy ensures that energy consumption will drop significantly in all countries, albeit in different degrees and at different costs. Region- or country-specific priority setting could support the development of strategies for reaching 2050 goals in different regions with lowered costs.

Dynamic TCT models can support the development of realistic country-specific or region-specific targets and of adequate policies to reach them. A TCT approach allows to identify (i) those parts of the stock where renovation is to produce the largest energy gains, and (ii) when to prioritize the construction of highly efficient buildings.

4.3. Germany and Czech Republic: Closing remarks

In Germany, the largest energy gains are to be expected from the deep renovation of the existing stock rather than from new highly energy efficient buildings. To exploit this potential most effectively, renovation activities must prioritize SFH and MFH built between 1920 and 1990. Alternatively, NZEB may become increasingly important if early demolition of old dwellings is promoted. Then, NZEB should be prioritized in the SFH segment if current housing preferences continue.

In contrast, the Czech residential stock is still in an early stage of development. Thus, most effective policies for energy gains are those addressing both old and new dwellings. Energy reductions can be maximized by (i) prioritizing renovation of AB built between

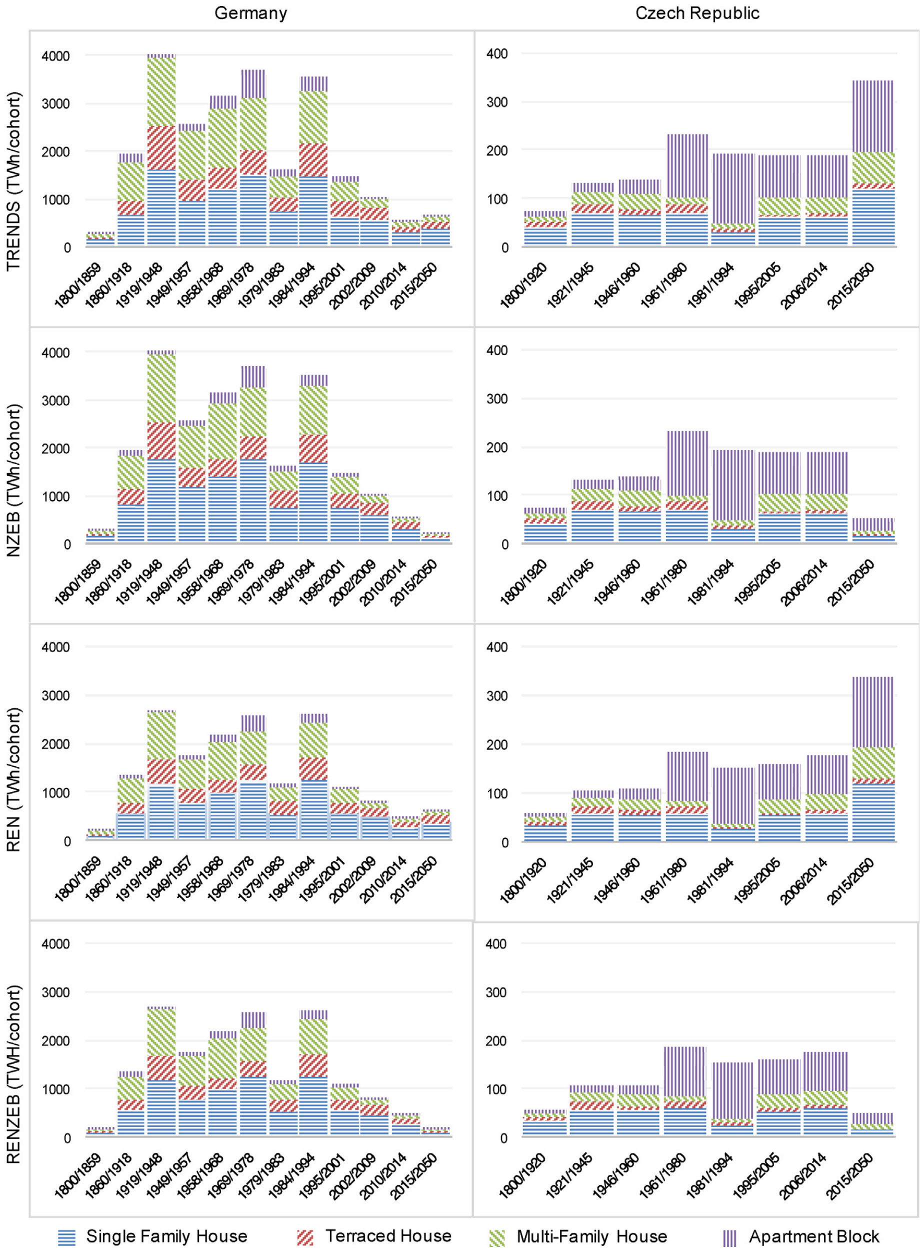


Fig. 9. Cumulative energy demand in TW h for the period 2015–2050 by dwelling types and cohort groups in the TRENDS, NZEB, REN and RENZEB scenarios (top to bottom).

1960 and 1990 (post WWII and during the cusp of the communist era), and (ii) by prioritizing NZEB also in AB if current housing preferences continue.

4.4. Uncertainties and limitations

Uncertainty and variability of energy results depend on energy policies and stock development. Uncertainty exploration with regards to energy policies is done via the four assessed scenarios (each assuming different *Energy Intensity of the Dwellings*, ε) where inclusion of alternative policy scenarios remains a possibility. All of these four scenarios assume the same stock development based on the five remaining parameters (P, $FApC$, TS, τ and σ). Accordingly, the uncertainty in the stock development variables (S, ΔS, I, O and λ) depends on the uncertainty of these parameters. Bergsdal et al. [66] and Sandberg et al. [107], who used dynamic modelling approaches similar to ours, concluded that the stock development results are most sensitive to changes in population and dwellings' lifetime, rather than lifestyle-related parameters. Accordingly, we discuss population and lifetime with some more detail in the following two subsections, while a more general discussion of the remaining parameters and other general issues regarding uncertainties is presented afterwards.

4.4.1. Population assumptions

Historical data on population is of low uncertainty as it is based on good quality sources like national statistical offices and the UN (United Nations). On the contrary, the future development of population is of large uncertainty. The variability in the UN low and high fertility scenarios with respect to the medium scenario, in 2050 and 2100, are in average of ±12% and ±49% for Germany, and of ±12% and ±45% for Czech Republic [108]. These uncertainties could be assigned to the forecasted stock size in the same periods as changes in population affect the size in a 1:1 ratio. This high uncertainty is particularly important in the German case where population decline rather than FApC growth drives the stock development. An increasing population situation in Germany could counteract the forecasted decline and recession in construction. In general, changes in migratory policies, fertility, and the economy can drastically affect the future need for buildings.

4.4.2. Lifetime and renovation cycles

The mean lifetime affects the magnitude of construction and demolition in time, which indirectly determines the composition of the stock. Renovation cycles, as modelled here, affect the energy intensity of the dwellings, whose uncertainty was addressed in the form of scenarios. Five different lifetimes were tested in each country during the process of model calibration (see Appendix A3). While different lifetimes did not imply significant variations in the construction trends of the past and present, the future presents a different situation. In Germany, when using lifetimes between 100 and 200 years, variations of up to +100% and between 0 and 4.4 million square-meters in construction were found in 2020 and 2050, respectively. Czech Republic exhibits average variations of ±10% in 2020 and of ±20% in 2050 when using lifetimes between 80 and 160 years. While the uncertainty levels are larger in Germany, this is mitigated by a good model calibration (Fig. 4). On the contrary, the uncertainty levels in Czech Republic are very significant because it is expected that mostly new dwellings drive energy demand after mid-century (Fig. 7). Propagation of these uncertainty levels to the energy results was not studied.

Lifetime of buildings and renovation cycles are still poorly understood. While in each country all dwellings, regardless of the type and cohort, were assumed to have the same lifetime and renovation cycle, it is very likely that these vary across types and cohorts. Such variations could partially explain the miscalibration in the construction for Czech Republic. A halving in the renovation cycle (or a doubling in renovation rates) as modelled in the REN and REN-ZEB scenarios could be considered as highly unrealistic because of the costly and non-mandatory nature of deep renovations. Some authors [59,65,107,109,110] have already started addressing these issues but the knowledge gap is still very wide.

4.4.3. Floor area per capita and type split of construction

FApC values of the past and present are to be regarded as highly certain due to the availability of statistics (Fig. 2). While this is not the case for the future, lower uncertainty levels are expected in Germany than in Czech Republic because the former country has started to show some signs of stabilisation in the service level as previously discussed in Section 2.3.

Regarding the type split of construction, the assumption of a constant split in the future construction activity involves a high uncertainty. This assumption is particularly relevant in the case of the Czech Republic where the housing stock is expected to grow rapidly, and where raising income levels may shift people's preferences from apartment blocks (particularly Panelaky from the communist era) to single family houses.

The impact of assumptions in both parameters for energy demand is more relevant in the TRENDS and REN scenarios where different dwelling types perform differently throughout their lifetime and energy consumption is correlated to their size. For the two other scenarios the future FApC and TS become irrelevant after 2020 because all new buildings, independently of their type and size, are assumed to achieve a zero-energy performance level.

4.4.4. Demographics in Germany: Consequences for construction activity and energy

While the overall population in Germany is declining, there are large regional differences caused, among others, by the migration from east to west. Deilmann et al. [111] predicted a reduction of 23% in the eastern housing stock by 2050, and an increase of 6% between 2005 and 2020 in the western stock due to migratory phenomenon. Deilmann et al. [111] also suggests that a process of stabilization with increased percentage of vacancies will follow these predicted changes in the regional stocks.

Our model does not capture these regional differences and therefore likely underestimates vacancies and obsolescence (mainly in east) as well as construction activity (mainly in west), which results de facto in shorter lifetimes and a faster replacement of the existing stock, and consequently, a faster reduction in operational energy use than forecasted. However, the model validation (Fig. 4) indicates that the impact of the regional disparity was minor.

4.4.5. Uncertainty in construction in Czech Republic and consequences for energy demand

While the stock results for both countries and the construction results for Germany agree well with historical values, the construction results for Czech Republic does not (bottom-right in Fig. 4). Our model predicts a larger construction activity in recent decades than the one reported in statistics for Czech Republic; therefore it generates a younger stock than the one we would expect from these statistics. Consequently, and provided that the statistical data on construction activity are correct, the modelled stock is likely more energy efficient than in reality–newer buildings are more energy efficient than old ones.

The sharp and rapid fluctuation in the statistics of the Czech construction activity in the last 4 decades is not well understood. According to the Czech Statistical Office there was a stock increase of around 10 m^2/cap between 1970 and 2011, equivalent to an 82% increase in the service level in the same period. This growth cannot be properly explained by such oscillating construction, particularly when the population also grew during this period. We presume that there are inconsistencies in the way the stock size and construction activity were measured and reported.

There might be other factors not addressed by our model that could explain the mismatch between modelled and observed construction. These factors could be of economic (e.g. market prices, economic conjectures/crises/booms), political (e.g. housing policies during the communist era), or technical nature (e.g. differentiated lifetime between different cohort groups and/or dwelling types). Analysis of these is beyond the scope of this paper.

4.4.6. Differences between calculated delivered energy demand and historic final energy

The energy use in 2010 reported by Eurostat [106] is in the case of Germany 21% lower than the one calculated by our model, while it is 80% higher in the case of the Czech Republic (Fig. 6). This discrepancy between modelled and reported energy use may be explained by the following factors:

1. While statistics report final energy use for all household purposes, the model calculates theoretical delivered energy for heating and hot water only. Lighting, appliances, and cooking, which were excluded, consume in average 20% of the energy in households in Europe [6]. This could explain around a fourth of the gap in the case of Czech Republic, while it increases the discrepancy in Germany.
2. The theoretical delivered energy (calculated) is often higher than the real delivered one (measured), for example due to unheated rooms. Similarly, the relative difference between “calculated” and “measured” is not constant as it differs across cohorts, building size and over time.
3. The example buildings used in TABULA may not be representative for the corresponding type-cohort segments.

The size and composition of the dwelling stock may not be captured accurately for the year 2010. This can involve errors in the reported information or errors for individual years due to the curve fitting applied in the model calibration.

Acknowledgements

Authors would like to thank Maren Lundhaug and Vera Jelenova for their help at gathering and translating some of the Czech statistics, and to Stefan Pauiliuk for his help at translating and interpreting some of the German statistics.

Appendix A.

A.1. Model description

A complete list of the model’s parameters and variables is presented in Table A.1. The input-parameters and output-variables are studied in the following three dimensions: j—Type of dwellings, *c*—Cohorts, *t*—Time.

The developed stock-driven model is always constrained by the need of keeping at all times an exact (and minimum) stock that guarantees the provision of a desired or required service level. In the current application, the service-level is defined by the floor area per capita (FApC)—which represents the average living area per person in a given year. Consequently, the total population (*P*) of a year determines the total size of the stock (S) as follows:

$$S_t = P_t \cdot \mathrm{FApC}_t \tag{A.1}$$

The stock change (ΔS) of the year is the difference between the stock of that year and the one of the preceding year:

$$\Delta S_t = S_t - S_{t-1} \tag{A.2}$$

The total construction activity (*I*) of the year responds to the net addition to stock (ΔS) and the replacement of the dwellings demolished (*O*) during the year because they have reached the end of their service life:

$$I_t = \Delta S_t + O_t \tag{A.3}$$

If the stock decreased in the year of analysis (because of shrinking population and/or shrinking service level), the new construction would respond only to the replacement of the demolished buildings if there were a need for it. In case that the negative stock change were much larger than the demolition activity, there would not be need for new construction. When this situation occurs the model is constrained (see Eq. (A.4)) by setting construction equal to zero and by redefining the stock change to only respond to demolition. In this way a negative construction ($I < 0$) is avoided.

$$\text{If}\ldots \Delta S_t + O_t < 0\ldots\text{then}\, I_t = 0\ldots\text{and}\ldots \Delta S_t = O_t \tag{A.4}$$

Similarly, the stock must be adjusted to account for the now smaller stock change. This new stock is dealt by in a different variable denominated real stock (S') (see Eq. (A.5)). The real stock is always larger than the theoretically required stock (*S* as in Eq. (A.1)), which means that an excess or vacant stock is generated. Then, *S* is to be regarded as “in-use stock” or “occupied stock” and S' as “total stock”. The vacant fraction of the stock is determined as in Eq. (A.6).

$$S'_t = S_{t-1} - \Delta S_t = S_{t-1} - O_t \tag{A.5}$$

$$\lambda_t = \frac{1 - S_t}{S'_t} \tag{A.6}$$

Whenever a zero-construction and vacant-stock situation occurs, the stock change of the following year must be calculated using the real stock (see Eq. (A.7)). This guarantees re-occupancy of vacant buildings over construction of new dwellings.

$$\Delta S_{t+1} = S_{t+1} - S'_t \tag{A.7}$$

The construction of a specific type of dwelling in a given year (the cohort year) is determined by share of the type in the total construction of the year (TS):

$$I_{j,t} = I_t \cdot \mathrm{TS}_{j,t} \tag{A.8}$$

which is otherwise explained by the following relationships:

$$\sum_j \mathrm{TS}_j = 1 \tag{A.9}$$

$$I_t = \sum_j I_{j,t} \tag{A.10}$$

The total demolition (*O*) of a year (see Eq. (A.11)) is the sum of the demolition of all individual preceding type-cohort segments of the stock. These individual demolitions (see Eq. (A.12)) are a function of the size of each type-cohort segment at construction (as in Eq. (A.8)) and the probability of being demolished (given its age). This

Table A.1
Model parameters and variables.

Symbol	Description	Dimensions	Unit	Type
P	Population	t	Cap	Parameter
FApC	Floor area per capita (living area)	T	m^2/cap	Parameter
TS	Type split of construction (share of a dwelling type in the year’s new constructions)	j, t	m^2/m^2	Parameter
τ	Expected average lifetime of dwellings	–	years	Parameter
σ	Lifetime standard deviation	–	years	Parameter
ε	Energy intensity of dwellings	j, c, t	kW h/m^2/year	Parameter
S	Stock of dwellings (minimum required = occupied)	j, c, t	m^2	Variable
S'	Real stock of dwellings (total stock = occupied + vacant)	j, c, t	m^2	Variable
ΔS	Stock change	j, c, t	m^2	Variable
I	Inflow of new dwellings (new constructions)	j, t	m^2	Variable
O	Outflow of dwellings (demolitions)	j, c, t	m^2	Variable
λ	Stock vacancy	T	m^2/m^2	Variable
E	Energy demand of the dwellings in use	j, c, t	kW h/year	Variable

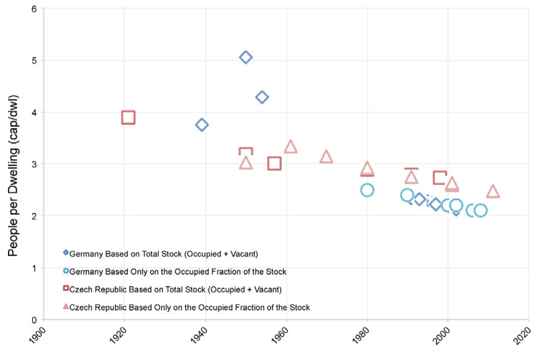


Fig. A1. People per Dwelling. *Sources:* [81,83–86,88–91].

probability is modelled using the probability density function of a normally distributed lifetime.

$$O_t = \sum_j \sum_c O_{j,c,t} \tag{A.11}$$

$$O_{j,c,t} = I_{j,c} \cdot f_{j,c,t} = I_{j,c} \cdot \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-((t-c)-\tau)^2/2\sigma^2} \tag{A.12}$$

Because demolition is a function of time (age), the standing stock of a specific type-cohort segment in a given year is determined by the accumulated demolition until that year (see Eq. (A.13)). Correspondingly, the total stock in a given year is the sum of the individual type-cohort segments up to that year:

$$S_{j,c,t} = I_{j,c} - \sum_{t=c}^{t} O_{j,c,t} \tag{A.13}$$

$$S_t = \sum_j \sum_c S_{j,c,t} \tag{A.14}$$

The stock given by Eq. (A.14) will always amount the total stock (as in Eq. (A.5)) whenever there exist vacant dwellings in the stock.

The total energy demand of a year (see Eq. (A.15)) is the sum of the energy demand of the individual type-cohort segments of the occupied standing stock. Vacant dwellings are deducted from the total energy demand by equally distributing the year's vacancy (λ) between all type-cohort segments of the stock.

$$E_t = \sum_j \sum_c S_{j,c,t} \cdot \varepsilon_{j,c,t} \cdot (1 - \lambda_t) \tag{A.15}$$

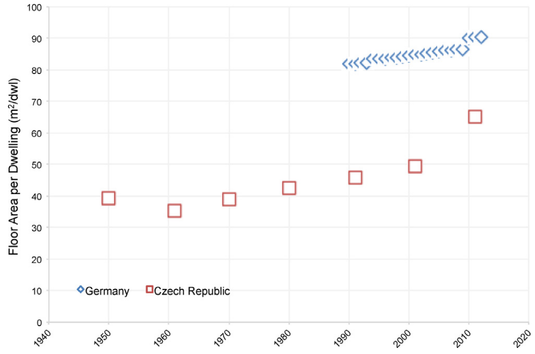


Fig. A2. Floor Area per Dwelling. Numbers follow the "Living Area" definition of each country and are based on the total stock (occupied + vacant). *Sources:* [80,81,87].

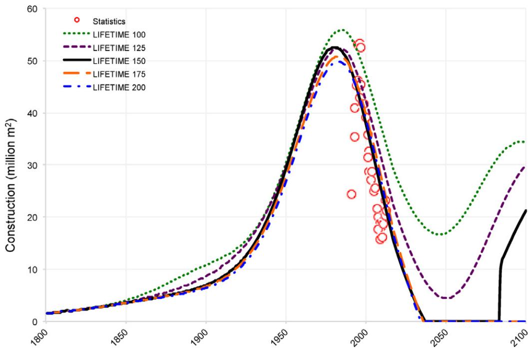


Fig. A3. Construction results to different dwelling's average service lifetime in Germany. Results are compared with historic available values from diverse sources [82–84,98–100].

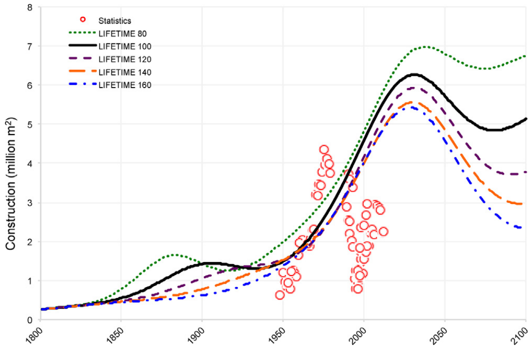


Fig. A4. Construction results to different dwelling's average service lifetime in Czech Republic. Results are compared with historic available values from diverse sources [82–84,90,96,97,99,101–104].

A.2. People per dwelling & floor area per dwelling

Figs. A1 and A2 show people per dwelling and floor area per dwelling historic numbers in Germany and Czech Republic. These were used as supporting information when defining the floor area per capita stabilisation level.

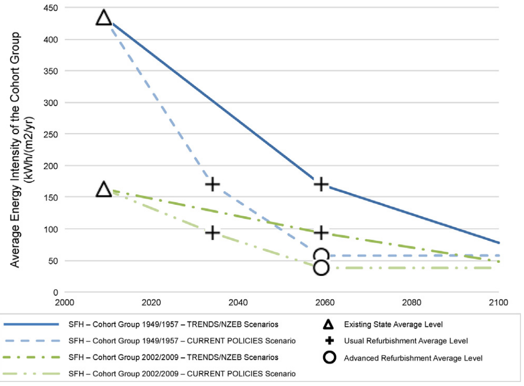


Fig. A5. Example of indirect modelling of renovation in Germany. Examples are given for the different modelled scenarios for a SFH of the cohort group 1949–1957 and a SFH of the cohort group of 2002–2009.

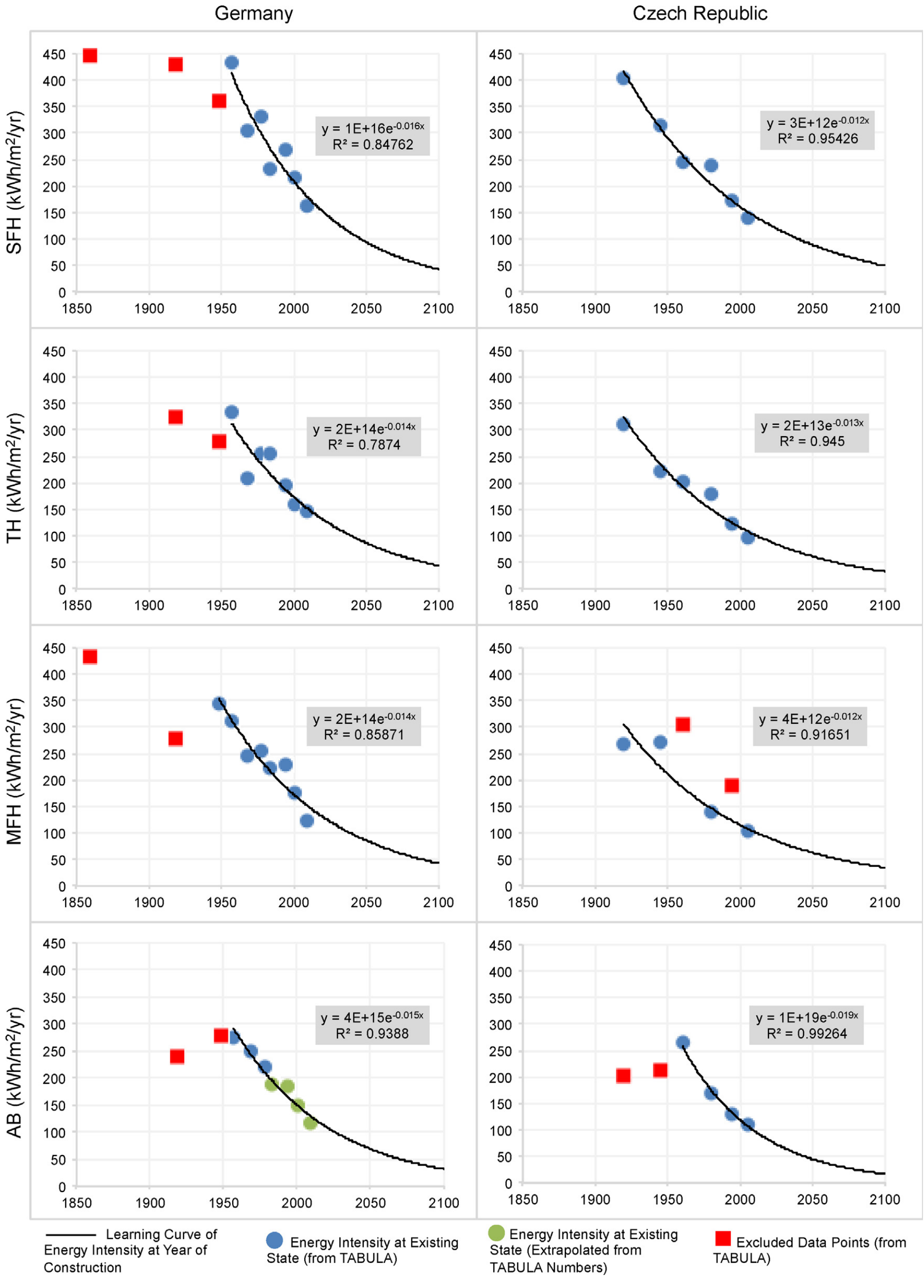


Fig. A6. Forecasted trendline for energy intensity at year of construction. Learning curve derived from values on Existing State energy performance level. The numbers excluded from the calculation are values that, although reported in TABULA, are excluded to improve the fitting (R^2) of the trendline. The trendline equations and R^2 presented in the grey boxes are derived from Excel using exponential trend/regression.

A.3. Construction results validation with different lifetimes

The model was calibrated to operate with an average lifetime of 150 and 100 years for German and Czech dwellings, respectively. These lifetimes were found to generate the construction results of best fit (validation) to statistical values. Discrepancies in the fit for Czech Republic are discussed in the main paper. The resulting construction when using other lifetimes is shown in Figs. A3 and A4 for Germany and Czech Republic, respectively.

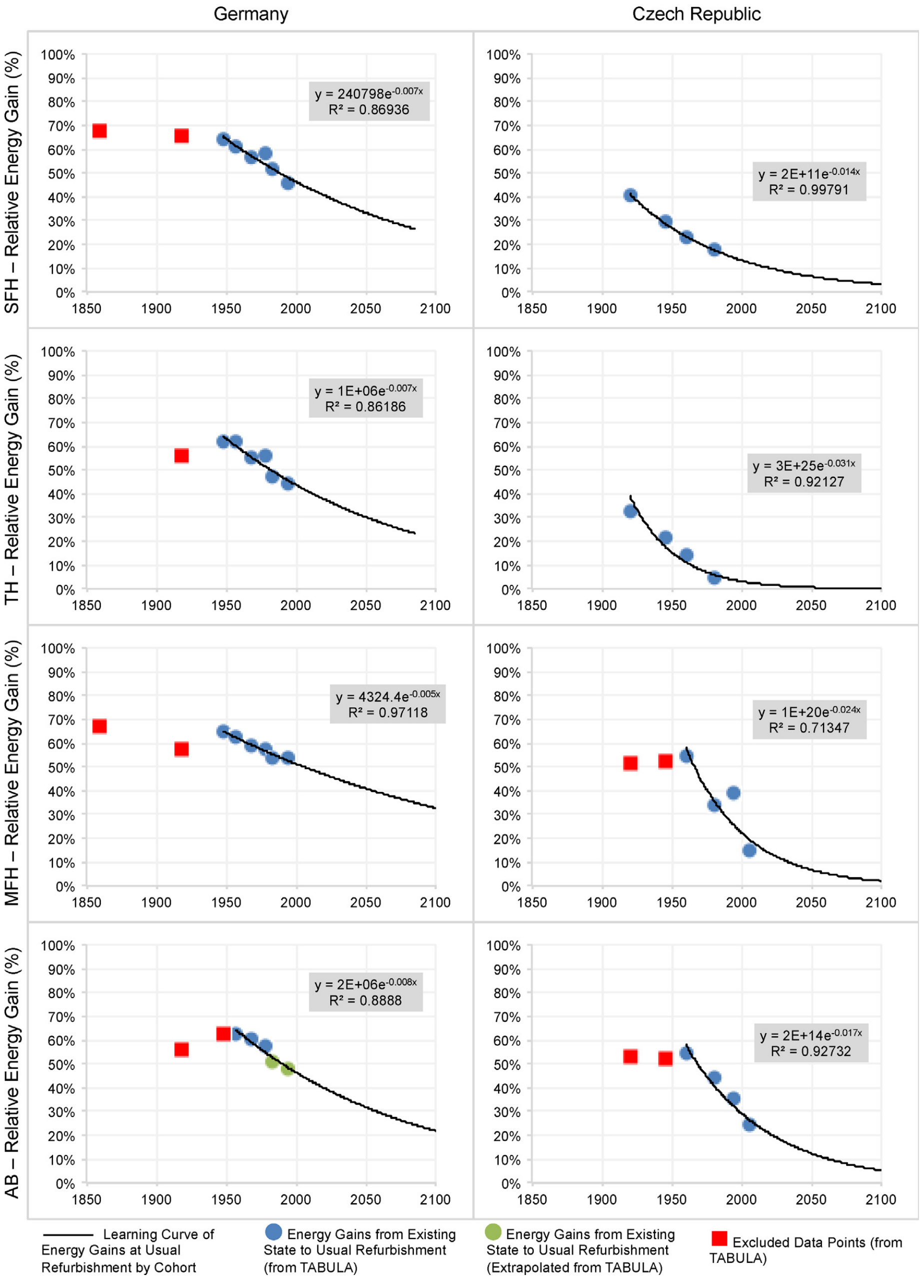


Fig. A7. Forecasted trendline for energy gains at usual refurbishment by cohort. Learning curve derived from values on calculated energy gains from the Existing State energy performance level to the Usual Refurbishment level. The numbers excluded from the calculation are calculated energy gains from TABULA values that are excluded to improve the fitting (R^2) of the trendline. The trendline equations and R^2 presented in the grey boxes are derived from Excel using exponential trend/regression.

A.4. Indirect modelling of renovation

Fig. A5 exemplifies the use of the different energy-intensity performance levels reported in TABULA [26] for indirect modelling of renovation. Each level set the average energy intensity of each type-cohort-group combination at a different point in time (according to each scenario). Linear transition from one average-energy-performance-level to another was assumed as an indirect way to represent renovation (see Fig. A5).

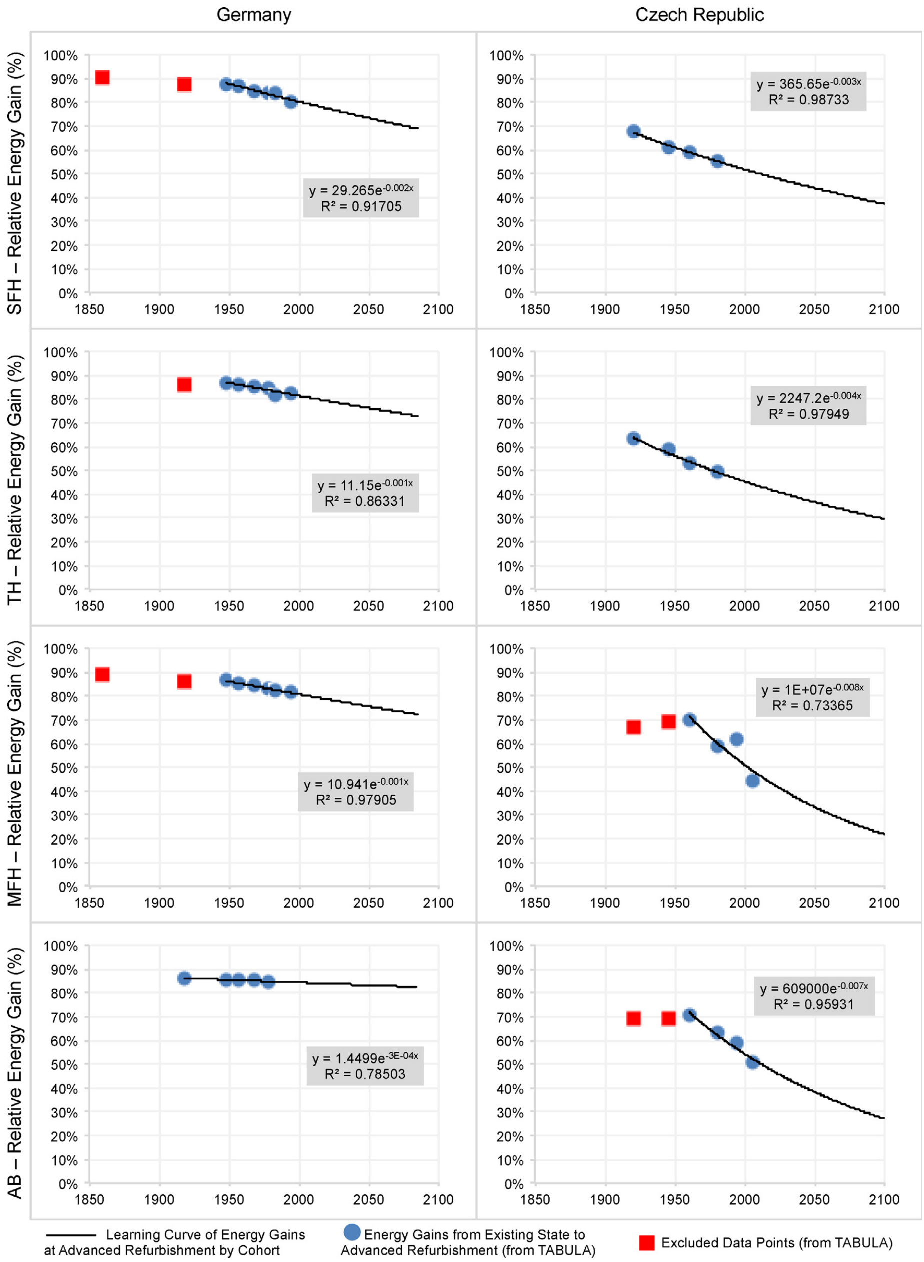


Fig. A8. Forecasted trendline for energy gains at advanced refurbishment by cohort. Learning curve derived from values on calculated energy gains from the Existing State energy performance level to the Advanced Refurbishment level. The trendline equations and R^2 presented in the grey boxes are derived from Excel using exponential trend/regression.

A.5. Learning curves for future cohorts in TRENDS scenario

Three technology learning curves were derived for each dwelling type in each country in order to define the energy intensity in each energy performance level of the future cohorts in the TRENDS scenario. These learning curves are trendlines with exponential fit to historical values, and were calculated in Excel. The different energy-intensity values of each cohort group were used as historical values. Each cohort group value was assumed to belong to the year of the last cohort of the cohort group. The first curve (see Fig. A6) defines the energy intensity at year of construction of the new cohorts. The two other set the cohort-dependent energy gains

Table A.2
Stock composition and distribution by types in Germany and Czech Republic in 2010.

Type	Germany		Czech Republic	
	Area (m^2)	%	Area (m^2)	%
SFH	1.44E + 09	42	6.97E + 07	29
TH	6.36E + 08	18	1.66E + 07	7
MFH	1 .13E + 09	32	3.55E + 07	15
AB	2.69E + 08	8	1.22E + 08	50
Total	**3.47E + 09**	**100**	**2.44E + 08**	**100**

at usual and advanced refurbishment levels. The gains trendlines are based on calculated energy gains from the different type-cohort-groups' energy performance levels in TABULA. Trendlines for usual refurbishment gains (Fig. A7) and advanced refurbishment gains (Fig. A8) were built on the premise that it is always true that lower relative energy gains are achieved in a newer cohort when compared to an older cohort when subjected to same equivalent refurbishments (in terms of usual or advanced as in TABULA). The drawback of this assumption is that we are always constraining the possibility of modelling energy-plus dwellings (energy self-sufficient dwellings–NZEB—that in addition deliver energy to the grid) by means of TRENDS.

A.6. Stock composition and distribution by types in 2010

Table A.2. presents the modelling results for the stock composition by type of dwelling for Germany and Czech Republic in 2010.

References

[1] IPCC, Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, USA, 2014.

[2] LuconF O., D. Ürge-Vorsatz, A. Zain Ahmed, H. Akbari, P. Bertoldi, L.F. Cabeza, et al., Buildings, in: O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, et al. (Eds.), Clim. Chang. 2014 Mitig. Clim. Chang. Contrib. Work. Gr. III to Fifth Assess. Rep. Intergov. Panel Clim. Chang., Cambridge University Press, Cambridge, UK and New York, USA, 2014, ⟨http://report.mitigation2014.org/drafts/final-draft-postplenary/ipcc_wg3_ar5_final-draft_postplenary_chapter9.pdf⟩.

[3] European Parliament, The council of The European Union, directive 2012/27/EU on energy efficiency, Off. J. Eur. Union 55 (2012) 1–56, http://dx.doi.org/10.3000/19770677.L_2012.315.eng.

[4] European Commission, Communication from the Commission to The European Parliament, The Council, The European Economic and Social Committee and The Committee of The Regions: Energy 2020 A strategy for competitive, sustainable and secure energy—COM(2010) 639, 2010, ⟨http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52010DC0639&from=EN⟩.

[5] European Parliament, The council of The European Union, directive 2010/31/EU on the energy performance of buildings (recast), Off. J. Eur. Union 53 (2010) 13–35, http://dx.doi.org/10.3000/17252555.L_2010.153.eng.

[6] European Commission, The Commission's new Energy Efficiency Plan—MEMO/11/149, 2011, ⟨http://europa.eu/rapid/press-release_MEMO-11-149_en.htm?locale=en⟩.

[7] European Commission, Communication from the Comission to The European Parliament, The Council, The European Economic and Social Committee and The Committee of The Regions: A Roadmap for moving to a competitive low carbon economy in 2050—COM(2011) 112, 2011, ⟨http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0112:FIN:EN:PDF⟩.

[8] European Commission, Financing the Energy Renovation of Buildings with Cohesion Policy Funding, 2014, http://dx.doi.org/10.2833/18766.

[9] K.C. Seto, S. Dhakal, A. Bigio, H. Blanco, G.C. Delgado, D. Dewar, et al., Human settlements, infrastructure and spatial planning, in: O. Edenhofer, R. Pichs-Madruga, Y. Sokona, FarahaniF E., S. Kadner, K. Seyboth, et al. (Eds.), Clim. Chang. 2014 Mitig. Clim. Chang. Contrib. Work. Gr. III to Fifth Assess. Rep. Intergov. Panel Clim. Chang., Cambridge University Press, Cambridge, UK and New York, USA, 2014.

[10] J.E. Anderson, G. Wulfhorst, W. Lang, Energy analysis of the built environment—a review and outlook, Renewable Sustainable Energy Rev. 44 (2015) 149–158, http://dx.doi.org/10.1016/j.rser.2014.12.027.

[11] N. Kohler, U. Hassler, The building stock as a research object, Build. Res. Inf. 30 (2002) 226–236, http://dx.doi.org/10.1080/09613210110102238.

[12] U. Hassler, Long-term building stock survival and intergenerational management: the role of institutional regimes, Build. Res. Inf. 37 (2009) 552–568, http://dx.doi.org/10.1080/09613210903189533.

[13] D.B. Müller, Stock dynamics for forecasting material flows—case study for housing in The Netherlands, Ecol. Econ. 59 (2006) 142–156, http://dx.doi.org/10.1016/j.ecolecon.2005.09.025.

[14] R.W. Amstalden, M. Kost, C. Nathani, D.M. Imboden, Economic potential of energy-efficient retrofitting in the Swiss residential building sector: the effects of policy instruments and energy price expectations, Energy Policy 35 (2007) 1819–1829, http://dx.doi.org/10.1016/j.enpol.2006.05.018.

[15] S. Salat, Energy loads, CO_2 emissions and building stocks: morphologies, typologies, energy systems and behaviour, Build. Res. Inf. 37 (2009) 598–609, http://dx.doi.org/10.1080/09613210903162126.

[16] M. Aydinalp-Koksal, V.I. Ugursal, Comparison of neural network, conditional demand analysis, and engineering approaches for modeling end-use energy consumption in the residential sector, Appl. Energy 85 (2008) 271–296, http://dx.doi.org/10.1016/j.apenergy.2006.09.012.

[17] Y. Shimoda, T. Fujii, T. Morikawa, M. Mizuno, Residential end-use energy simulation at city scale, Build. Environ. 39 (2004) 959–967, http://dx.doi.org/10.1016/j.buildenv.2004.01.020.

[18] E. Cuerda, M. Pérez, J. Neila, Facade typologies as a tool for selecting refurbishment measures for the Spanish residential building stock, Energy Build. 76 (2014) 119–129, http://dx.doi.org/10.1016/j.enbuild.2014.02.054.

[19] A. Parekh, Development of archetypes of building characteristics libraries for simplified energy use evaluation of houses, in: Ninth Int. IBPSA Conf., Montreal, Canada, 2005.

[20] Y.J. Huang, J. Brodrick, A Bottom-up Engineering Estimate of the Aggregate Heating and Cooling Loads of the Entire U.S. Building Stock, 2000, ⟨http://www.escholarship.org/uc/item/5hv2t661⟩.

[21] P.J. Jones, S. Lannon, J. Williams, Modelling building energy use at urban scale, in: Seventh Int. IBPSA Conf, Rio Janeiro, Brazil, 2001, pp. 175–180.

[22] L.G. Swan, V.I. Ugursal, I. Beausoleil-Morrison, Occupant related household energy consumption in Canada: estimation using a bottom-up neural-network technique, Energy Build. 43 (2011) 326–337, http://dx.doi.org/10.1016/j.enbuild.2010.09.021.

[23] F. Nemry, A. Uihlein, C.M. Colodel, C. Wetzel, A. Braune, B. Wittstock, et al., Options to reduce the environmental impacts of residential buildings in the European Union-Potential and costs, Energy Build. 42 (2010) 976–984, http://dx.doi.org/10.1016/j.enbuild.2010.01.009.

[24] J. Tornberg, L. Thuvander, A GIS energy model for the building stock of Goteborg, in: 25th ESRI Int User Conf., 2005, ⟨http://proceedings.esri.com/library/userconf/proc05/papers/pap2244.pdf⟩.

[25] J.-P.A. Snäkin, An engineering model for heating energy and emission assessment the case of North Karelia, Finland, Appl. Energy 67 (2000) 353–381, http://dx.doi.org/10.1016/S0306-2619(00)00035-0.

[26] Institut Wohnen und Umwelt GmbH, Joint EPISCOPE and TABULA Website, 2014, 2014, ⟨http://episcope.eu⟩.

[27] E.G. Dascalaki, K.G. Droutsa, C.a. Balaras, S. Kontoyiannidis, Building typologies as a tool for assessing the energy performance of residential buildings—a case study for the Hellenic building stock, Energy Build. 43 (2011) 3400–3409, http://dx.doi.org/10.1016/j.enbuild.2011.09.002.

[28] B.M. Larsen, R. Nesbakken, Household electricity end-use consumption: results from econometric and engineering models, Energy Econ. 26 (2004) 179–200, http://dx.doi.org/10.1016/j.eneco.2004.02.001.

[29] T. Hong, C. Koo, H. Kim, H. Seon Park, Decision support model for establishing the optimal energy retrofit strategy for existing multi-family housing complexes, Energy Policy 66 (2014) 157–169, http://dx.doi.org/10.1016/j.enpol.2013.10.057.

[30] A. Capasso, W. Grattieri, R. Lamedica, A. Prudenzi, A bottom-up approach to residential load modeling, IEEE Trans. Power Syst. 9 (1994) 957–964, http://dx.doi.org/10.1109/59.317650.

[31] R. Choudhary, Energy analysis of the non-domestic building stock of Greater London, Build. Environ. 51 (2012) 243–254, http://dx.doi.org/10.1016/j.buildenv.2011.10.006.

[32] M. Aydinalp, V. Ismet Ugursal, A.S. Fung, Modeling of the space and domestic hot-water heating energy-consumption in the residential sector using neural networks, Appl. Energy 79 (2004) 159–178, http://dx.doi.org/10.1016/j.apenergy.2003.12.006.

[33] L.G. Swan, V.I. Ugursal, I. Beausoleil-Morrison, Hybrid residential end-use energy and greenhouse gas emissions model–development and verification for Canada, J. Build. Perform. Simul. 6 (2011) 1–23, http://dx.doi.org/10.1080/19401493.2011.594906.

[34] G. Dall'O', A. Galante, G. Pasetti, A methodology for evaluating the potential energy savings of retrofitting residential building stocks, Sustainable Cities Soc. 4 (2012) 12–21, http://dx.doi.org/10.1016/j.scs.2012.01.004.

[35] R. Haas, L. Schipper, Residential energy demand in OECD-countries and the role of irreversible efficiency improvements, Energy Econ. 20 (1998) 421–442, http://dx.doi.org/10.1016/S0140-9883(98)00003-6.

[36] J. Bentzen, T. Engsted, A revival of the autoregressive distributed lag model in estimating energy demand relationships, Energy 26 (2001) 45–55, http://dx.doi.org/10.1016/S0360-5442(00)00052-9.

[37] A.F. Emery, C.J. Kippenhan, A long term study of residential home heating consumption and the effect of occupant behavior on homes in the Pacific

Northwest constructed according to improved thermal standards, Energy 31 (2006) 677–693, http://dx.doi.org/10.1016/j.energy.2005.04.006.

[38] R. Kadian, R.P. Dahiya, H.P. Garg, Energy-related emissions and mitigation opportunities from the household sector in Delhi, Energy Policy 35 (2007) 6195–6211, http://dx.doi.org/10.1016/j.enpol.2007.07.014.

[39] I. Sartori, B.J. Wachenfeldt, A.G. Hestnes, Energy demand in the Norwegian building stock: scenarios on potential reduction, Energy Policy 37 (2009) 1614–1627, http://dx.doi.org/10.1016/j.enpol.2008.12.031.

[40] R. Nesbakken, Price sensitivity of residential energy consumption in Norway, Energy Econ. 21 (1999) 493–515, http://dx.doi.org/10.1016/S0140-9883(99)00022-5.

[41] H. Tommerup, S. Svendsen, Energy savings in Danish residential building stock, Energy Build. 38 (2006) 618–626, http://dx.doi.org/10.1016/j.enbuild.2005.08.017.

[42] H. Farahbakhsh, V.I. Ugursal, A.S. Fung, A residential end-use energy consumption model for Canada, Int. J. Energy Res. 22 (1998) 1133–1143, doi:10.1002/(SICI)1099-114X(19981025)22:13<1133::AID-ER434>3.0.CO;2-E.

[43] L. Itard, F. Meijer, Towards a Sustainable Northern European Housing Stock: Figures, Facts, and Future, IOS Press, Amsterdam, The Netherlands, 2008, ISSN 1574-6410; 22 ISBN 978-1-58603-977-6.

[44] H.K. Ozturk, O.E. Canyurt, A. Hepbasli, Z. Utlu, Residential-commercial energy input estimation based on genetic algorithm (GA) approaches: an application of Turkey, Energy Build. 36 (2004) 175–183, http://dx.doi.org/10.1016/j.enbuild.2003.11.001.

[45] Buildings Performance Institute Europe, Europe's Buildings Under the Microscope, Build. Perform. Inst. Eur. (2011), ⟨http://bpie.eu/uploads/lib/document/attachment/20/HR_EU_B_under_microscope_study.pdf⟩.

[46] N. Heeren, M. Jakob, G. Martius, N. Gross, H. Wallbaum, A component based bottom-up building stock model for comprehensive environmental impact assessment and target control, Renewable Sustainable Energy Rev. 20 (2013) 45–56, http://dx.doi.org/10.1016/j.rser.2012.11.064.

[47] N.C. Onat, G. Egilmez, O. Tatari, Towards greening the U.S. residential building stock: a system dynamics approach, Build. Environ. 78 (2014) 68–80, http://dx.doi.org/10.1016/j.buildenv.2014.03.030.

[48] N. Kohler, B. Schwaiger, B. Barth, M. Koch, Mass flow, energy flow and costs of the German building stock, in: CIB 2nd Int. Conf Build. Environ., CSTB, Paris, France, 1997, pp. 9–12.

[49] J. Palmer, B. Boardman, C. Bottrill, S. Darby, M. Hinnells, G. Killip, et al., Reducing the Environmental Impact of Housing: Final Report, Environmental Change Institute, University of Oxford, 2006, http://healthimpactassessment.pbworks.com/f/Reducing+the+environmental+impact+of+housing+-+RCEP+UK+-+2006.pdf.

[50] C. Petersdorff, T. Boermans, J. Harnisch, Mitigation of CO_2 Emissions from the EU-15 Building Stock. Beyond the EU Directive on the Energy Performance of Buildings (9 pp), Environ. Sci. Pollut. Res. 13 (2006) 350–358, http://dx.doi.org/10.1065/espr2005.12.289.

[51] U.S. Energy Information Administration, Residential Demand Module of the National Energy Modeling System: Model Documentation 2013, U.S. Energy Information Administration, Washington, DC, 2013, ⟨http://www.eia.gov/forecasts/aeo/nems/documentation/residential/pdf/m067(2013).pdf⟩.

[52] T. Siller, M. Kost, D. Imboden, Long-term energy savings and greenhouse gas emission reductions in the Swiss residential sector, Energy Policy 35 (2007) 529–539, http://dx.doi.org/10.1016/j.enpol.2005.12.021.

[53] H. Hens, G. Verbeeck, B. Verdonck, Impact of energy efficiency measures on the CO_2 emissions in the residential sector, a large scale analysis, Energy Build 33 (2001) 275–281, http://dx.doi.org/10.1016/S0378-7788(00)00092-X.

[54] Department of Electrical Engineering, National Energy Efficiency Action Plan of the Czech Republic, 2014, ⟨http://ec.europa.eu/energy/sites/ener/files/documents/NEEAPCzechRepublic_en2014.pdf⟩.

[55] R. McKenna, E. Merkel, D. Fehrenbach, S. Mehne, W. Fichtner, Energy efficiency in the German residential sector: a bottom-up building-stock-model-based analysis in the context of energy-political targets, Build. Environ. 62 (2013) 77–88, http://dx.doi.org/10.1016/j.buildenv.2013.01.002.

[56] K. Bettgenhäuser, Integrated Assessment Modelling for the German Building Sector—A Technical, Economical and Ecological Analysis, 2013, pp. 1–17.

[57] K. Bettgenhäuser, Integrated Assessment Modelling for Builing Stocks—A Technical, Economical and Ecological Analysis, Ingenieurwissenschaftlicher Verlag, Bonn, Germany, 2013.

[58] T. Boermans, K. Bettgenhäuser, M. Offermann, S. Schimschar, Renovation Tracks for Europe up to 2050, 2012.

[59] J.L. Reyna, M.V. Chester, The growth of urban building stock, J. Ind. Ecol. 00 (2014) n/a–n/a, http://dx.doi.org/10.1111/jiec.12211.

[60] N.H. Sandberg, H. Bergsdal, H. Brattebø, Historical energy analysis of the Norwegian dwelling stock, Build. Res. Inf. 39 (2011) 1–15, http://dx.doi.org/10.1080/09613218.2010.528186.

[61] N.H. Sandberg, H. Brattebø, Analysis of energy and carbon flows in the future Norwegian dwelling stock, Build. Res. Inf. 40 (2012) 123–139, http://dx.doi.org/10.1080/09613218.2012.655071.

[62] D.B. Müller, H.-P. Bader, P. Baccini, Long-term coordination of timber production and consumption using a dynamic material and energy flow analysis, J. Ind. Ecol. 8 (2004) 65–88, http://dx.doi.org/10.1162/1088198042442342.

[63] S. Pauliuk, K. Sjöstrand, D.B. Müller, Transforming the Norwegian dwelling stock to reach the 2 degrees celsius climate target, J. Ind. Ecol. 17 (2013) 542–554, http://dx.doi.org/10.1111/j.1530-9290.2012.00571.x.

[64] C. Gallardo, N.H. Sandberg, H. Brattebø, Dynamic-MFA examination of Chilean housing stock: long-term changes and earthquake damage, Build. Res. Inf. (2014) 1–16, http://dx.doi.org/10.1080/09613218.2014.872547.

[65] N.H. Sandberg, I. Sartori, H. Brattebø, Using a dynamic segmented model to examine future renovation activities in the Norwegian dwelling stock, Energy Build. 82 (2014) 287–295, http://dx.doi.org/10.1016/j.enbuild.2014.07.005.

[66] H. Bergsdal, H. Brattebø, R.A. Bohne, D.B. Müller, Dynamic material flow analysis for Norway's dwelling stock, Build. Res. Inf. 35 (2007) 557–570, http://dx.doi.org/10.1080/09613210701287588.

[67] I. Sartori, H. Bergsdal, D.B. Müller, H. Brattebø, Towards modelling of construction, renovation and demolition activities: Norway's dwelling stock, 1900–2100, Build. Res. Inf. 36 (2008) 412–425, ⟨http://www.scopus.com/inward/record.url?eid=2-s2.0-49549114046&partnerID=tZOtx3y1⟩ (accessed August 28, 2014).

[68] M. Hu, H. Bergsdal, E. van der Voet, G. Huppes, D.B. Müller, Dynamics of urban and rural housing stocks in China, Build. Res. Inf. 38 (2010) 301–317, http://dx.doi.org/10.1080/09613211003729988.

[69] M. Hu, E. Van Der Voet, G. Huppes, Dynamic material flow analysis for strategic construction and demolition waste management in Beijing, J. Ind. Ecol. 14 (2010) 440–456, http://dx.doi.org/10.1111/j.1530-9290.2010.00245.x.

[70] M. Hu, S. Pauliuk, T. Wang, G. Huppes, E. van der Voet, D.B. Müller, Iron and steel in Chinese residential buildings: a dynamic analysis, Resour. Conserv. Recycl. 54 (2010) 591–600, http://dx.doi.org/10.1016/j.resconrec.2009.10.016.

[71] ISO, ISO 13790:2008(E)—Energy Performance of Buildings—Calculation of Energy Use for Space Heating and Cooling, 2008, ⟨www.iso.org⟩.

[72] Český Statistický Úřad, Obyvatelstvo—roční časové řady, 2014, 2013, ⟨http://www.czso.cz/csu/redakce.nsf/i/obyvatelstvo_hu⟩.

[73] Ministerstvo Práce a Sociálních Věcí, Prognóza populačního vývoje České republiky, 2008–2070, 2010, pp. 2014, ⟨http://www.mpsv.cz/cs/8838⟩.

[74] Statistisches Bundesamt Weisbaden, Germany's Population by 2060, Results of the 12th coordinated population projection, 2014, 2009, ⟨https://www.destatis.de/EN/Publications/Specialized/Population/GermanyPopulation2060.pdf?__blob=publicationFile⟩.

[75] Statistisches Bundesamt Weisbaden, Bevölkerungsprojektion: Bevölkerung (Mill.), mittlere Vorausberechnungsvariante, 2014, 2013, ⟨https://www.destatis.de/DE/ZahlenFakten/LaenderRegionen/Internationales/Land/G20/TabelleBevoelkerungsprojektion.html⟩.

[76] U. Pfister, G. Fertig, The Population History of Germany: Research Strategy and Preliminary Results, in: MPIDR Work. Pap. WP 2010-035. 2014, 2010, ⟨http://www.demogr.mpg.de/papers/working/wp-2010-035.pdf⟩.

[77] Statistisches Bundesamt Weisbaden, Statistisches Jahrbuch—Ältere Ausgaben, 2014, 2014, ⟨https://www.destatis.de/DE/Publikationen/StatistischesJahrbuch/StatistischesJahrbuch_AeltereAusgaben.html⟩ (accessed April 29, 2014).

[78] Friedrich Ebert Stiftung, Die Versorgung der Deutschen mit Wohnungen, 2014 (1999), ⟨http://library.fes.de/fulltext/stabsabteilung/00518.htm#E9E1⟩.

[79] United Nations Economic Commission for Europe, The Housing Situation in European Countries Around 1960: A Statistical Survey, United Nations, New York, NY, 1963.

[80] Statistisches Bundesamt Weisbaden, Wohnungsbestand in Deutschland, 2013, ⟨https://www.destatis.de/DE/ZahlenFakten/Wirtschaftsbereiche/Bauen/Bautaetigkeit/Tabellen/WohnungsbestandDeutschland.html⟩ (accessed April 29, 2014).

[81] Český Statistický Úřad, Czech Demographic Handbook 2012, 2013, ⟨http://www.scitani.cz/csu/2013edicniplan.nsf/engp/4032-13⟩ (accessed April 28, 2014).

[82] Helgi Analytics, Real Estate Indicators, 2014, ⟨http://www.helgilibrary.com/indicators⟩ (accessed March 15, 2014).

[83] United Nations Economic Commission for Europe, Bulletin of Housing and Building Statistics for Europe and North America 2000, 2000, ⟨http://www.unece.org/hlm/prgm/hsstat/Bulletin_00.html⟩ (accessed March 16, 2014).

[84] United Nations Economic Commission for Europe, Bulletin of Housing Statistics for Europe and North America 2004, 2004, ⟨http://www.unece.org/hlm/prgm/hsstat/Bulletin_04.html⟩ (accessed March 16, 2014).

[85] United Nations Economic Commission for Europe, The European Housing Situation, United Nations, 1955.

[86] Ministry of the Interior and Kingdom Relations, Housing Statistics in the European Union 2010, 2010.

[87] Statistisches Bundesamt Weisbaden, Gebäude und Wohnungen: Bestand an Wohnungen und Wohngebäuden, Bauabgang von Wohnungen und Wohngebäuden, Lange Reihen ab 1969–2012, Statistisches Bundesamt, Weisbaden, 2014, ⟨https://www.destatis.de/DE/Publikationen/Thematisch/Bauen/Wohnsituation/FortschreibungWohnungsbestandPDF_5312301.pdf?__blob=publicationFile⟩.

[88] L'Office de Statistique de la République Tchécoslovaque, T.S.O. of the C. Republic, Manuel Statistique de la République Tchécoslovaque, Prague, 1925.
[89] Orbis, T.S.O. of the C. Republic, Statistická ročenka Republiky Československé 1957, Orbis, Praha, 1957.
[90] Český Statistický Úřad, C.S. Office, Statistická ročenka České republiky 2013, 2013, ⟨https://www.czso.cz/csu/czso/statisticka-rocenka-ceske-republiky-2013-pxygncc90n⟩ (accessed March 15, 2014).
[91] United Nations Economic Commission for Europe, Bulletin of Housing Statistics for Europe and North America 2006, 2006, ⟨http://www.unece.org/hlm/prgm/hsstat/Bulletin_06.html⟩ (accessed March 16, 2014).
[92] A. Uihlein, P. Eder, Policy options towards an energy efficient residential building stock in the EU-27, Energy Build. 42 (2010) 791–798, http://dx.doi.org/10.1016/j.enbuild.2009.11.016.
[93] T. Kristjansdottir, H. Fjeldheim, E. Selvig, B. Time, L. Georges, T.H. Dokka, et al., A Norwegian ZEB-Definition Embodied Emission, SINTEF Academic Press, Oslo, 2014, ⟨http://www.zeb.no/index.php/reports/item/559-a-norwegian-zeb-definition-embodied-emission⟩.
[94] Federal Environment Ministry of Germany, Climate Agenda 2020: Restructuring Industrial Society, 2007.
[95] Buildings Performance Institute Europe, Country Factsheets: Data Hub for the Energy Performance of Buildings, 2012, ⟨http://www.buildingsdata.eu/country-factsheets⟩ (accessed March 15, 2014).
[96] Federální Statistický Úrad, Český Statistický Úrad, Slovenský Statistický Urad, Statistická ročenka Československé Socialistické Republiky 1975, SNTL -Nakladatelství technické literatury, Praha, 1975.
[97] Federální Statistický Úrad, ÄŒeský Statistický Úrad, Slovenský Statistický Úrad, Statistická roÄ_enka ÄŒeskoslovenské Socialistické Republiky 1980, SNTL - Nakladatelství Technické Literatury, Praha, 1980.
[98] Statistisches Bundesamt Weisbaden, Building Activity: Construction work completed in Germany, 2014, 2014, ⟨https://www.destatis.de/EN/Facts Figures/EconomicSectors/Construction/BuildingActivity/Tables/Construction Work.html⟩.
[99] United Nations Economic Commission for Europe, Bulletin of Housing and Building Statistics for Europe and North America 2002, 2002, ⟨http://www.unece.org/hlm/prgm/hsstat/Bulletin_02.html⟩ (accessed March 16, 2014).
[100] Statistisches Bundesamt Weisbaden, Bauen und Wohnen: Baugenehmigungen/Baufertigstellungen, Lange Reihen z. T. ab, 1949, 2014, ⟨https://www.destatis.de/DE/Publikationen/Thematisch/Bauen/Bautaetigkeit Wohnungsbau/BaugenehmigungenBaufertigstellungenPDF_5311101.pdf;jsessionid=98BABB911EA5FE60FE065F38F1ADC119.cae4?__blob=publication File⟩.
[101] Český Statistický Úřad, C.S. Office, Statistická ročenka České republiky 2008, 2014, 2009, ⟨http://www.czso.cz/csu/2008edicniplan.nsf/publ/0001-08-2008⟩.
[102] Český Statistický Úřad, C.S. Office, Statistická ročenka České republiky 2004, 2014, 2004, ⟨http://www.czso.cz/csu/2004edicniplan.nsf/publ/10n1-04-_2004⟩.
[103] Český Statistický Úřad, Czech Statistical Office, Česká republika od roku 1989 v číslech 2014, 2013, ⟨http://www.czso.cz/csu/redakce.nsf/i/cr_od_roku_1989#11⟩.
[104] Ústřední Komise Lidové Kontroly A Statistiky, Statistická ročenka Československé Socialistické Republiky 1965, Státní Nakladatelství Technické Literatury, Praha, 1965.
[105] Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, General information—Energy Efficiency, 2013, ⟨http://www.bmub.bund.de/en/topics/climate-energy/energy-efficiency/general-information/#c15246⟩ (accessed December 14, 2014).
[106] Eurostat, Final Energy Consumption by Sector—Residential, 2014, ⟨http://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=tsdpc320⟩ (accessed September 20, 2014).
[107] N.H. Sandberg, I. Sartori, H. Brattebø, 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. 85 (2014) 136–144, http://dx.doi.org/10.1016/j.enbuild.2014.09.028.
[108] United Nations Department of Economic and Social Affairs Population Division, World Population Prospects: The 2012 Revision, 2013, ⟨http://esa.un.org/unpd/wpp/Excel-Data/population.htm⟩.
[109] S. Huuhka, J. Lahdensivu, Statistical and geographical study on demolished buildings, Build. Res. Inf. (2014) 1–24, http://dx.doi.org/10.1080/09613218.2014.980101.
[110] P. Erik Bradley, N. Kohler, Methodology for the survival analysis of urban building stocks, Build. Res. Inf. 35 (2007) 529–542, http://dx.doi.org/10.1080/09613210701266939.
[111] C. Deilmann, K.-H. Effenberger, J. Banse, Housing stock shrinkage: vacancy and demolition trends in Germany, Build. Res. Inf. 37 (2009) 660–668, http://dx.doi.org/10.1080/09613210903166739.
[112] D. Ürge-Vorsatz, N. Eyre, P. Graham, D. Harvey, E. Hertwich, Y. Jiang, et al., Energy End-Use: Building, in: Glob. Energy Assess.—Towar. A Sustain. Futur., Cambridge University Press and the International Institute for Applied Systems Analysis, Cambridge, UK and New York, NY, USA and Laxenburg, Austria, 2012, pp. 649–760, ⟨www.globalenergyassessment.org⟩ Chapter 10.

Paper 2

Dwelling stock dynamics for addressing housing deficit.

Olaya, Y., **F. Vásquez**, and D.B. Müller. 2017. *Resources, Conservation and Recycling* 123: 187–199. http://dx.doi.org/10.1016/j.resconrec.2016.09.028.

Resources, Conservation and Recycling 123 (2017) 187–199

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Dwelling stock dynamics for addressing housing deficit

Yris Olaya[a,*], Felipe Vásquez[b], Daniel B. Müller[b]

[a] Universidad Nacional de Colombia, Cra 80 No. 65-223 Medellín, Colombia
[b] Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), 7491, Trondheim, Norway

ARTICLE INFO

Article history:
Received 15 April 2016
Received in revised form
22 September 2016
Accepted 22 September 2016
Available online 19 October 2016

Keywords:
Stock dynamics
Housing deficit
Colombia
Construction
Demolition
Dwellings

ABSTRACT

Housing in developing countries is often inadequate due to overcrowding, lack of suitable shelter, lack of sanitation and exposure to natural hazards. The United Nations classifies these conditions into two types of deficit: quantitative and qualitative. Strategies for eliminating housing deficits need to consider the dynamics of the total dwelling stock in order to balance this objective with other goals, such as employment in the construction sector, costs, and environmental impacts. Existing dwelling stock models were developed mainly for developed countries and are not suitable to address housing deficits. Here we use a case study for Colombia's housing stock to propose a dynamic stock model that incorporates deficit. We analyze the evolution of the stock under twelve scenarios combining three projections for household growth and four trajectories for eliminating deficit. The model is calibrated using census data, UN population projections, and own appraisals of household size, based on historical trends. Our results show that closing all deficits by 2030 would require upgrading 2.8 to 3.3 million existing dwellings and building 3.6 to 6.3 million new dwellings, depending on demographics. This represents an increase of 97–155% in construction activity. Conversely, if deficit stays at the current 31% level, 5.1 to 7.9 million households would be in deficit by 2030.

1. Introduction

1.1. Housing deficit in the developing world and Colombia

Most developing countries exhibit higher rates of population growth than developed countries, and have experienced rapid urbanization (Cohen, 2004). In many parts of the world, this growth has been decoupled from economic growth (Cohen, 2004) which has resulted on growing informal settlements, and large numbers of households with unsatisfied housing needs (UN-Habitat, 2003).

In 2012 UN-Habitat (2012a) estimated that 863 million people lived in slums; corresponding to 32.7% of the urban population in developing regions. The largest shares of slum population appear in Sub-Saharan Africa (65%), Southern Asia (45%), South Eastern Asia (39%), and Eastern Asia (37.4%), followed by Latin American and the Caribbean (29%) (Statista, 2016; UN-Habitat, 2012a; UNSD, 2015). For the latter region, the Inter-American Development Bank estimated that 37% of households in 2009 had unsatisfied housing needs (Bouillon et al., 2012b). Low household income, labor informality, high interest rates, and high cost of land and materials are some of the barriers that prevent access to formal housing (Bouillon et al., 2012a) and explain the prevalence of inadequate housing in developing countries.

Colombia is a case representative of the housing conditions observed in other developing nations. First, fast urbanization, sustained population and economic growth, and high inequality (Ortiz and Cummins, 2011; World Bank, 2016) have created housing needs that are inappropriately satisfied because there are considerable access barriers, particularly to land and financing (Bouillon et al., 2012b). Second, ownership is preferred over renting because investing in housing is perceived as a way to save and create family wealth (Gilbert, 2001). Nonetheless, income inequality in Colombia is among the highest in Latin America and the world (World Bank, 2016), and most of the population has no access to housing credit (Murcia Pabón, 2007). Housing policies that promote financing rules and increase access to credit through demand subsidies and interest rate subsidies (Fique Pinto, 2008), have limited impact because 47% of labor is informal (Dane, 2016).

Like many developing nations, Colombia has had a long-term historical mismatch between demographic growth and housing availability. Colombia is the third most populated country in South America with an estimated population of 48,2 million by 2015 (United Nations, 2015). Between 1950 and 2005 the Colombian

---

* Corresponding author.
E-mail addresses: yolayam@unal.edu.co (Y. Olaya), luis.v.correa@ntnu.no (F. Vásquez), daniel.mueller@ntnu.no (D.B. Müller).

http://dx.doi.org/10.1016/j.resconrec.2016.09.028
0921-3449/

population increased twofold, at declining growth rates. Following a trend observed in developed and other Latin American countries, household size decreased from 5.8 to 3.9 persons per household between 1950 and 2005 (United Nations, 1974; DANE, 2005). While population growth and household size decline caused total households in 2005 to increase by a 3.7 factor with respect to 1950, the dwelling stock growth lagged behind, increasing unsatisfied housing needs (DANE, 2005).

For policy and accounting purposes, unsatisfied housing needs are referred to and measured as "housing deficit". Housing deficit is measured as number of households. Households are defined as arrangements of one or more persons who "make common provision for food or other essentials for living" (United Nations, 2014). Qualitative deficit accounts for dwellings with deficient conditions (materials, space, and basic services) that can be improved, and quantitative deficit refers to dwellings with non-remediable overcrowding and structural deficiencies (DANE, 2008). As these definitions are ambiguous and deficit measures rely on normative assessments of quality and overcrowding, deficit estimations are subject to high uncertainty (Monkkonen, 2013). Colombia's latest census in 2005 reported housing deficit at 36% expressed as 12% quantitative and 24% qualitative (DANE, 2005). Although housing deficit decreased 1.5 points per year between 1993 and 2005, during the same period, the number of households with deficits remained practically unchanged, with a 0.34% decrease (CENAC, n.d.). These figures show that housing policies in Colombia have failed at attending population with housing deficits.

Housing policies in Colombia have followed a similar path as those in other Latin American countries (Bouillon et al., 2012b; Murray and Clapham, 2015), evolving from financial mechanisms created in the 1950s to interest rate subsidies and cash transfers 1950-date. Historically, these policies have especially increased housing provision for middle-income households (Gilbert, 2014), but have failed to cover households below the national poverty line, which account for 78% of housing deficit (ONU-Habitat, 2012). In 2012 a radically different policy of building 100 thousand free dwellings for poor households was adopted (Congreso de Colombia, 2012).

1.2. Modelling dwelling stock dynamics and housing needs

Understanding the state, composition and dynamics of dwelling stocks is necessary to evaluate the impact that strategies for closing deficits have on construction materials consumption and demolition waste management, among other factors. The importance of dwelling stock dynamics has been extensively discussed in the literature in the light of: (i) socioeconomic and quality of life concerns, (ii) climate change and energy use, (iii) material use and resource efficiency, and (iv) construction, demolition, renovation and land use planning (Kohler and Hassler, 2002; Lucon et al., 2014; ONU-Habitat, 2015; Schiller, 2007; Seto et al., 2014; UN-Habitat, 2012b, 2003; Ürge-Vorsatz et al., 2012).

Correspondingly, a variety of approaches has been proposed and used for building stocks' research as reviewed by Swan and Ugursal (Swan and Ugursal, 2009) and Kavgic et al. (2010). Vásquez et al. (2016) also presented a detailed review of studies on the topic, and found that most comprehensive studies for the investigation of the building stocks' long-term dynamics and externalities employ a stock-driven approach. Stock-driven models, common in the Material Flow Analysis (MFA) field, have supported the study of construction, demolition, renovation, and material and energy use in developed and developing countries (Bergsdal et al., 2007; Gallardo et al., 2014; Hu et al., 2010a, 2010b, 2010c; Müller, 2006; Pauliuk et al., 2013; Sandberg et al., 2011, 2014a, 2014b; Sandberg and Brattebø, 2012; Sartori et al., 2009, 2008; Vásquez et al., 2016).

Developed and developing countries have similar problems with planning and resources use, which justifies the use of the same modeling approaches. However, the economic and social conditions of developing countries pose unique challenges for modeling building stocks. In particular, current MFA models are not designed for addressing issues related to large and growing populations living in substandard dwellings. Only four studies that use stock-driven models for developing countries were found: three cases on China (Hu et al., 2010a,b; Huang et al., 2013), one that differentiates urban and rural dynamics and two that focus on materials; and a fourth case on Chile (Gallardo et al., 2014) that incorporates earthquake vulnerability and damage.

MFA models that represent the conditions of developing countries can contribute to the formulation and evaluation of housing policies that address problems particular to these countries. In this paper we develop a stock driven model that estimates the construction and renovation activity needed to close quantitative and qualitative deficits under different socio-demographic scenarios and at different time horizons. This is a first step for estimating the materials and resources needed to satisfy future housing needs in developing countries with housing deficiencies. We apply the model to the case of Colombia, which is representative of upper-middle income developing countries.

2. Method

2.1. System definition

Fig. 1 describes the system and depicts the stocks and flows of households and dwellings. Both stocks are differentiated by three types of housing deficit conditions: No Deficit (ND), Qualitative Deficit (QL), and Quantitative Deficit (QN), according to the UN definitions (ONU-Habitat, 2015).

Two kinds of household flows are distinguished. First, inflows or outflows to the stock, driven by sociodemographic growth, which are internalized in the stock change of each type. And second, internal flows between types. The latter are two unidirectional flows from qualitative (QL) and quantitative (QN) to no (ND) deficit. The system is defined for the evaluation of policies that aim at closing the deficit gap, thus deterioration of household conditions is not studied.

Three kinds of dwelling flows are studied: constructions, demolitions, and upgrades. Constructions and demolitions represent inflows and outflows to and from the stock, respectively. Demolitions include those dwellings reaching the end of their service life plus the vacant dwellings with non-remediable deficiencies (QN), which are assumed to be always demolished because they are (i) inadequate for housing and (ii) built with flimsy materials. Upgrades is a unidirectional flow that only applies to qualitative-deficit (QL) dwellings entering the no deficit (ND) stock. This change of type implies refurbishment or remodeling of the dwellings.

2.2. Model description

A dynamic *type-cohort-time* model was developed for this study. It combines the stock-driven and the activity-driven approaches in standard MFA methods, and it makes use of a discrete difference-equations system. It builds on the modeling principles for residential building stocks introduced by Müller (2006) and discussed and extended by Vásquez et al. (2016). A 251-year time frame (1850–2100) is defined to allow for the accumulation of gradual changes in dwelling stock size and distributions of type and age. These changes are caused by slow changes in demographics and lifestyle, and by the long lifetime of buildings. By modeling a stock with a closer resemblance with reality, we enhance the applicabil-

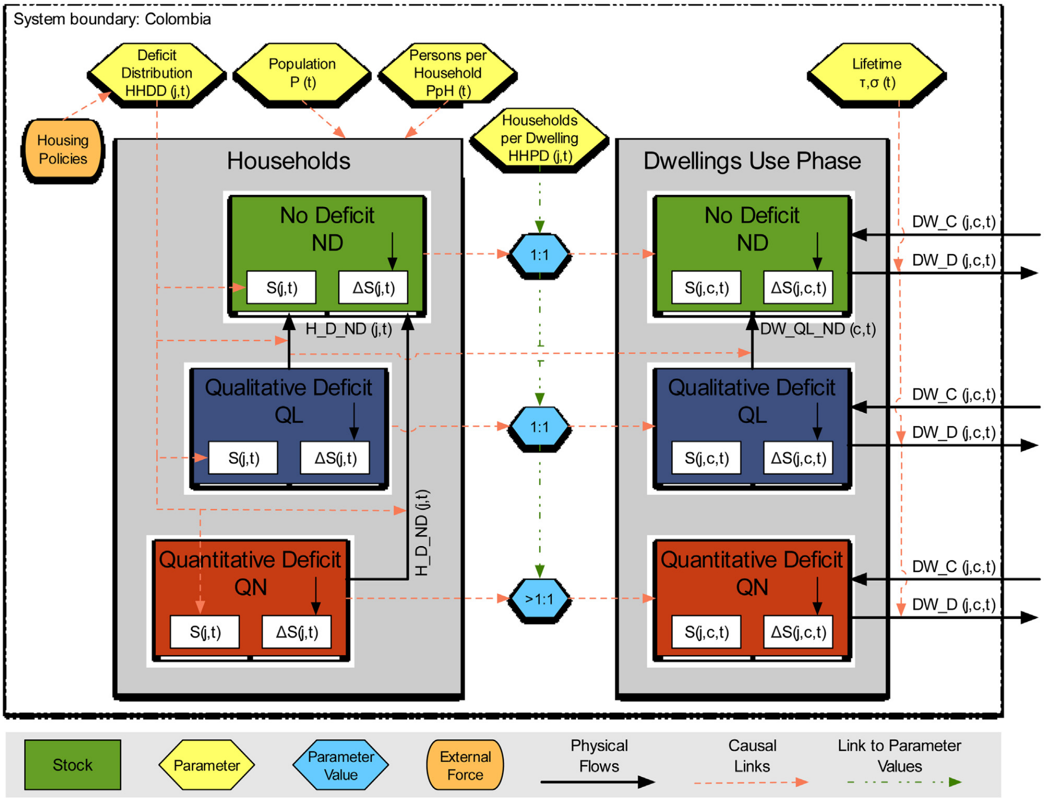


Fig. 1. System and model definition. Variables: S – Stock, ΔS – Stock Change, H_D_ND – Flow of Households to No Deficit, DW_C – Constructions, DW_D – Demolitions, DW_QL_ND – Upgrades. Dimensions: j – type, c – cohort, t – time. Lifetime's Mean (τ) and Standard Deviation (σ).

ity of the model to answer long-term sustainability and other policy questions. The last year, 2100, corresponds to the most commonly used in the current climate change discourse (Intergovernmental Panel on Climate Change, 2014) and dynamic MFA applications and studies. The model has a *Household Module* and a *Dwelling Module*. A detailed model description is presented in Supplementary information S1.

The *Household Module* is a stock-driven model that tracks flows of households through all deficit types. The stock dynamics are driven by three exogenous socioeconomic variables: Population (*P*), Persons per Household (*PpH*), and Household Deficit Distribution (*HHDD*). Four output variables are generated for the three deficit types (*j*) over time (*t*): Stock of Households (*H*), Households Stock Change (*ΔH*), Households Demographic Change (*ΔH_dem*), and Flow of Households from Qualitative and Qualitative Deficits to No Deficit (*H_D_ND*).

The stock (*H*) is defined by the population (*P*) and the average persons per household (*PpH*). Its composition is regulated by the household deficit distribution (*HHDD*) as follows:

$$H_{j,t} = \frac{P_t}{PpH_t} \cdot HHDD_{j,t} \tag{1}$$

The stock change of each type (see Eqs. (2) and (3)) is defined by (i) its internal demographic change and (ii) the flows between types. The latter flows correspond to the inflows to ND from QL and QN as in the rightmost term in Eq. (2); or conversely to the outflows from QL and QN towards ND as in the rightmost term in Eq. (3).

$$\Delta H_{j=ND,t} = \Delta H\_dem_{j=ND,t} + \sum_{j|\{QL,QN\}} H\_D\_ND_{j,t} \tag{2}$$

$$\Delta H_{j|\{QL,QN\},t} = \Delta H\_dem_{j,t} - H\_D\_ND_{j,t} \tag{3}$$

The households' demographic change represents the increase (formation of new households) or decrease (dissolution of existing households) in the total number of households. This change is assumed to occur across all household types, and proportionally to the type distribution of the previous year (see Eq. (4)).

$$\Delta H\_dem_{j,t} = \Delta H_t \cdot HHDD_{j,t-1} \tag{4}$$

The flows of households from QL and QN to ND (rightmost term in Eq. (3)) result from balancing their corresponding stock change and demographic change so the household deficit distribution of the year is achieved.

The *Dwelling Module* is a dynamic stock-and-activity-driven model that tracks flows of dwellings through all type-cohort fractions of the dwelling stock. The stock dynamics are driven by three parameters and two endogenous variables. The parameters are: Households per Dwelling (*HHPD*), Mean Lifetime of Dwellings (τ), and Lifetime Standard Deviation (σ). *HHPD* is representative of socioeconomic conditions while τ and σ are representative of the buildings' technology and management, and other external factors.

The endogenous variables are: Household Stock (*H*), and Flow of Households from Qualitative and Qualitative Deficit to No Deficit (*H_D_ND*), from the household module.

Nine output variables are generated: Stock of Dwellings (*DW*), Dwellings Stock Change (*ΔDW*), Constructions (*DW_C*), Constructions in No Deficit for Households from Quantitative Deficit (*DW_C_ND_QN*), Upgrades of Dwellings from Qualitative Deficit to No Deficit (*DW_QL_ND*), Total Demolitions (*DW_D*), Demolitions Due to End-Of-Service-Life (*DW_D_age),* Planned Demolitions of Vacant/Excess Dwellings from Quantitative Deficit (*DW_D_QN*), and Vacant Dwellings (*DW_V*). Dwelling variables are studied in three dimensions: by Type of Deficit (*j*), by Cohort (*c*), and in Time (*t*) on a yearly basis. Each cohort corresponds to one specific year.

The stock of dwellings (*DW*) is defined by the households (*H*) and the average number of households per dwelling (*HHPD*) for each type of household (see Eq. (5)). The stock change of each dwelling type is explained by the balance of the (i) demolition, (ii) upgrading, and (iii) construction flows, as expressed in Eqs. (6), (7) and (8) for ND, QL and QN respectively.

$$DW_t = \sum_j DW_{j,t} = \sum_j \frac{H_{j,t}}{HHPD_{j,t}} \tag{5}$$

$$\Delta DW_{j=ND,t} = DW\_C_{j=ND,t} + DW\_QL\_ND_t - DW\_D\_age_{j=ND,t} \tag{6}$$

$$\Delta DW_{j=QL,t} = DW\_C_{j=QL,t} - DW\_QL\_ND_t - DW\_D\_age_{j=QL,t} \tag{7}$$

$$\Delta DW_{j=QN,t} = DW\_C_{j=QN,t} - DW\_D\_age_{j=QN,t} - DW\_D\_QN_t \tag{8}$$

Two kinds of demolition flows are considered: (i) end-of-service-life (EOL), and (ii) planned demolition. The EOL demolitions of a type-cohort segment responds to (i) the number of constructed dwellings in the segment, and (ii) their probability of being demolished given their age (see Eq. (9)). This probability is modelled by using the probability density function of a normally-distributed lifetime.

$$DW\_D\_age_{j,c,t} = DW\_C_{j,c} \cdot \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-((t-c)-\tau)^2/2\sigma^2} \tag{9}$$

Planned demolitions, which are only considered for QN dwellings, equal the totality of vacant QN dwellings at the end of the year. Again, vacant dwellings represent a surplus that occurs when the standing dwellings exceed the residential needs, resulting in no need for construction.

Upgrading only applies to QL dwellings. The amount of dwellings to upgrade (see Eq. (10)) is driven by the number of households that flow from QL to ND. The latter are assumed to preserve the households-per-dwelling ratio of the previous year when changing type.

$$DW\_QL\_ND_t = \frac{H\_D\_ND_{j=QL,t}}{HHPD_{j=QL,t-1}} \tag{10}$$

Construction per type of dwellings is calculated according to Eqs. (6), (7), and (8), so the stock change of each type is achieved once demolitions and upgrades have occurred.

Lastly, we quantify the number of ND dwellings resulting from the households moving from QN to ND – for policy analysis purposes – as follows:

$$DW\_C\_ND\_QN_t = \frac{H\_D\_ND_{j=QN,t}}{HHPD_{j=ND,t}} \tag{11}$$

3. Data and scenarios

To capture uncertainty in model's inputs, we define twelve scenarios by combining three households (*H*) series and four alternative paths for closing deficits (*HHDD*).

3.1. Household series: population and persons per household

3.1.1. Household series

Households High, Medium and Low in Table 1, are derived from selected combinations of population (*P*) and persons per household (*PpH*) projections (see Fig. 2), which are based on historical data and estimates from the Colombian Department of Statistics (DANE) and the UN (DANE, 2005; United Nations, 2015, 1980, 1974).

Data for household size are inconsistently reported, as indicated by series 'Data' in Fig. 2 (right). According to census data, during the 20th century, the average household size in Colombia decreased from 5.8 in 1964 to 3.9 in 2005. However, there are no available statistics prior 1950. Thus, a complete synthetic "Historical" series (1850–2005) was obtained by regressing the data at hand which was complemented with an appraisal for the household size in 1850 (see Fig. 2, right). The 1850's estimate was derived by averaging a sample of U.S. and European values from a variety of sources for years between 1787 and 1881 to better reflect the living conditions of the time. We avoid the extrapolation of the 1950–2005 trends towards 1850 because social and economic conditions in the second half of the 20th century are too different from the conditions in the second half of the 19th century.

There are no census data for average household size in Colombia after 2005, yet we expect that the observed general trend of declining household size continues until 2100, when it begins to stabilize. However, because the household size depends on uncertain social and economic factors, three plausible scenarios (PPH_HIGH, PPH_MED, and PPH_LOW in Fig. 2) were defined to deal with this uncertainty. These projections assume a logistic-shaped tendency towards stabilization as observed in developed countries, and only differ in the rate of household size decline and the household size value reached by 2100 (2.85, 2.51, and 2.09 persons per household).

The PPH_MED forecast assumes that convergence towards nuclear households starts in 1985, taking approximately 100 years to reach a 2.5 household size as in Bradbury et al. (2014). The PPH_LOW series represents a scenario in which faster economic behavior and social changes lead household size to reach a value of 2.17 persons per household by 2085, and of 2.09 by 2100. This figure is a conservative assessment, considering that household sizes in Europe decreased, on average, 0.021 per year between 1960 and 1980 (Keilman, 1987), and that countries like Denmark reached a 2.1 household size by 2013 (Denmark, 2013). Finally, the PHP_HIGH series assumes that household size decreases at a low rate, reaching a value of 2.93 by 2050, of 2.85 by 2085, and of 2.8 persons per household by 2150.

Variations in the persons per household (PpH) projections may seem small, in absolute terms, with respect to those in the population (P) projections. Yet, on a yearly basis, the number of households is equally sensitive to same relative changes in PpH or P. Differently, in the long term, because P projections vary more than PpH projections (see Fig. 2), most of the differences in household scenarios can be attributed to population growth. A complete sensitivity analysis is provided in the Supplementary information S5.

3.2. Alternative paths for closing housing deficits

Housing conditions in Colombia are assessed by the department of statistics using data from censuses and surveys and following the methodology described in DANE (2008). We used these assessments in combination with those from UN-Habitat (United Nations, 1980, 1974) to fit a logistic regression for the historical values of the quantitative (QN) and no deficit (ND) categories according to the current definition on deficit types (ONU-Habitat, 2015), which are reported as percentage of total households. Since deficit categories do not overlap (DANE, 2008), qualitative deficit (QL) was calculated

Table 1
Household series: selected combinations of population and persons per household projections.

Household series name	Population projection	Persons per household projection	Description
Households High	Upper_95_PI	PPH_LOW	High population growth, high number of households
Households Medium	Median_PI	PPH_MED	Median population growth, medium number of households
Households Low	Lower_95_PI	PPH_HIGH	Low population growth, low number of households

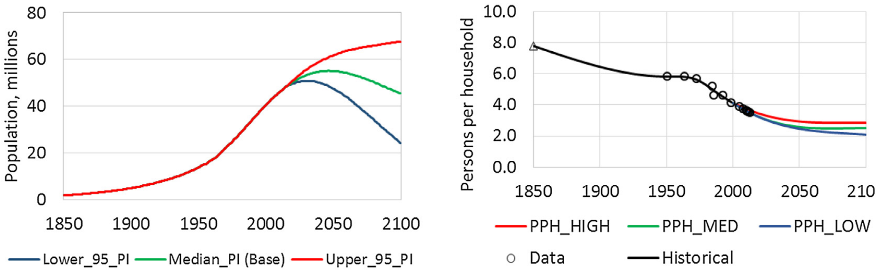
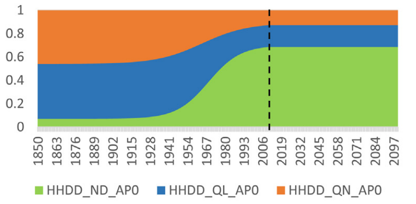
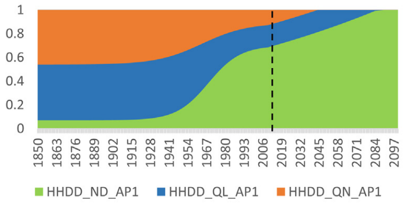
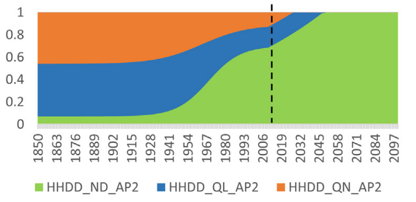
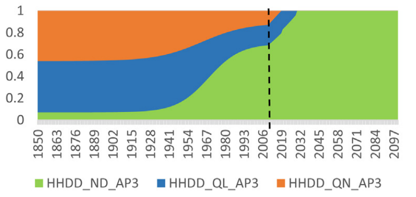


Fig. 2. Population (left) and persons per household (right) series, 1850–2100. Data from United Nations (2015, 1980, 1974) and DANE (2005).

Table 2
Alternative paths for housing deficit distribution.

Path description and assumptions	Housing deficit distribution (*HHDD*)
AP0: Constant deficit. Deficit distribution stays at present percentage levels.	
AP1 I. Households without deficit increase at a 0.005 annual rate. II. Quantitative deficit is alleviated first (flows from QN to ND). III. Quantitative deficit is 0% in 2045. IV. Flows from QL to ND start when QN = 0. V. Qualitative deficit is 0% in 2090.	
AP2 I. Households without deficit increase at a 0.01 annual rate. II. Quantitative deficit is alleviated first (flows from QN to ND). III. Quantitative deficit is 0% in 2030. IV. Flows from QL to ND start when QN = 0. V. Qualitative deficit is 0% in 2050.	
AP3 I. Households without deficit increase at a 0.015 annual rate II. Quantitative deficit is alleviated first (flows from QN to ND). III. Quantitative deficit is 0% in 2020. IV. Flows from QL to ND start when QN = 0. V. Qualitative deficit is 0% in 2030.	

as the remaining percentage (adding up to 100%). The resulting historic deficit distribution for the time 1850–2015 is presented in the figures in Table 2. The regression results for the latter estimates are presented in the Supplementary information S2–Fig. S2.1.

We define three alternative deficit distribution paths: AP1, AP2, and AP3. These paths represent the effect of possible policies for closing housing deficits at different target years, which indirectly drives the deficit-reduction rates. For comparison, we defined an additional path (AP0) in which deficit distribution remains at present levels. See Table 2 for a detailed description of the alternative paths – AP.

All deficit paths assume that housing policies address quantitative deficit first and are followed by measures to tackle qualitative deficit. Furthermore, we assume that these policies are sustained over time in such a way that new housing needs are always met. Our model has no economic inputs, but economic growth is implicit in the rates at which deficits are closed. In this sense, paths AP2 and AP3 assume faster economic growth than AP1, while AP0 represents a scenario in which economic growth is enough to prevent housing deficit to grow.

The alternative paths are proposed to evaluate the construction activity needed to close housing deficits in a given year, and do not intend to represent actual housing policies. Instead, these paths provide inputs for defining and benchmarking housing policies.

3.3. Data in the dwelling module

Dwelling stocks are derived from household stocks using the parameter “households per dwelling” as the main input. We use the data reported by DANE on average number of households per dwelling for the whole country (see Table 3) to fit a quadratic model (see Supplementary information S3), and estimate past and project future national average number of households per dwelling.

To estimate the occupation of dwellings with overcrowding (quantitative deficit), we assume that dwellings with no deficit and qualitative deficit are occupied by a single household (no overcrowding), and calculate the corresponding occupation of dwellings with quantitative deficit following Eq. (12).

$$HHPD_{j=QN,t} = \frac{H_{j=QN,t} \cdot HHPD_{National,t}}{H_t - HHPD_{National,t} \cdot \left(H_{j=ND,t} + H_{j=QL,t}\right)} \qquad (12)$$

Finally, we use a normal probability distribution N(100, 25) to model the expected lifetime of dwellings, similar to (Vásquez et al., 2016).

4. Results

4.1. Households dynamics

The number of households estimated for 2016 is approximately 14.2 million but future numbers vary across the High, Medium and Low household scenarios, and this variation increases with time (see top heading-row in Fig. 3). Households estimates for 2030 lie between 15.8 and 19.2 million whereas for 2100 the number of households ranges between 8.5 and 32.4 million.

Between 2016 and 2100 the number of households increases by 128% in the high scenario and by 27% in the medium one. In the same period, the number of households decreases by 40% in the low scenario. As Fig. 2 shows, population projections vary more than projected household size. Therefore, most of the differences in household scenarios are due to population growth (see sensitivity analysis in the Supplementary information S5).

In the Households High scenario the households stock grows continuously from 2016 to 2100, mainly because the average number of persons per household decreases (see Fig. S5.1). Contrary, in the Households Medium and Low scenarios households' stock shrinks because the decrease in household size is not enough to offset the population declines observed after 2040 and 2050.

Fig. 3 also shows that households with no deficit compose the majority of the stock under all deficit assumptions. Nevertheless, the magnitude and duration of this dominance varies greatly across scenarios and the numbers of households in deficit conditions remain significant in most of them, as illustrated in detail in Fig. S4.1 of Supplementary information S4.

The number of households with unsatisfied needs is larger with high population/small household size (Households High) than with low population/large household size (Households Low) because deficit depends directly on the expected number of households.

Under the path with constant deficit distribution (AP0), the number of households in deficit in the Households High scenario increases continuously from 4.5 million in 2016 to 6.1 million in 2030, to 7.9 million in 2050, and to 10.2 million in 2100. These figures are much higher than in the Households Low scenario in which the number of households in deficit increases to 5 million in 2030 and to 5.1 in 2050, and then falls to 2.7 million in 2100. In both Low and Medium scenarios the number of households in deficit increases until 2050, then it declines as a result of lower demographic pressure. This decline is very sharp in the Low scenario, where it causes a 48% reduction in number of households in deficit between 2050 and 2100.

By 2030, in the AP0 scenarios, there are between 16 and 33% more households in deficit than in 2016. By 2050 the deficit is between 18 and 73% higher than in 2016, and by 2100 between 48% lower and 29% higher than in 2016.

Demographic changes, reflected in population and household size, affect both the scope and results of housing policies. Ceteris paribus, housing policies need to target more households when household number are higher to stay on the same deficit path. Similarly, as Fig. 4 illustrates, fewer households need to be covered by policies when deficits are closed by 2030 (AP3) than by 2090 (AP1).

While between 2016 and 2030 most of the changes in households' deficit status result from the deficit path assumptions (see Fig. 4), after 2050 most of the deficit change in the Low scenario is explained by demographics. However, as Fig. 3 illustrates, housing deficits are not closed unless measures are adopted.

4.2. Dwelling stock dynamics

The long-term development of the dwelling stock is similar to the household stock development. The household stock shrinks after 2050 in all but in the Households High scenarios (see Fig. 5a and Fig. S4.2). This shrinking results in declining construction and increasing demolition rates. The total number of dwellings ranges between 15.2 and 25 million in 2050 and between 8.6 and 32.4 million in 2100. Consistent with household dynamics, the number of dwellings grows faster in the High scenarios than in the Low and Medium ones. In the latter scenarios, the stock of dwellings peaks in 2050 and subsequently declines until 2100.

Since household stocks are influenced by uncertain demographic and social changes, we look at the stock of dwellings in order to gain insight into the implications for housing policies.

As expected, deficit path AP0, which maintains the current deficit distribution, exhibits the largest number of deficit dwellings and it provides an upper bound for analysis. Fig. 5b (blue series) shows that, by 2030, between 1 and 1.2 millions of dwellings are overcrowded and/or unsafely built (QN), while the total number of dwellings without minimum services (QL) is between 3 and 3.6 million. Analogously, by 2050 the stock of QN and QL dwellings is between 1 and 1.6 million and between 3 and 4.7 million, respectively.

Table 3
Housing deficit and dwelling occupation statistics.

Year	Housing deficit No deficit ND	Quantitative QN	Qualitative QL	Average households per dwelling HHPD	Households per dwelling, quantitative deficit HHPD_QN	Sources
1951	23%	34%	43%	1.10	1.29	a
1964	31%	30%	39%	1.45	2.49	a
1973	42%	25%	33%	1.17	1.69	a
1985	57%	19%	24%			a
1991	63%	15%	22%			b
1993	69%	14%	17%	1.03	1.24	a
1995	66%	15%	19%			b
1996	67%	16%	17%			b
2005	64%	12%	24%	1.14	2.14	a

aSource DANE.
bSource UN-Habitat.

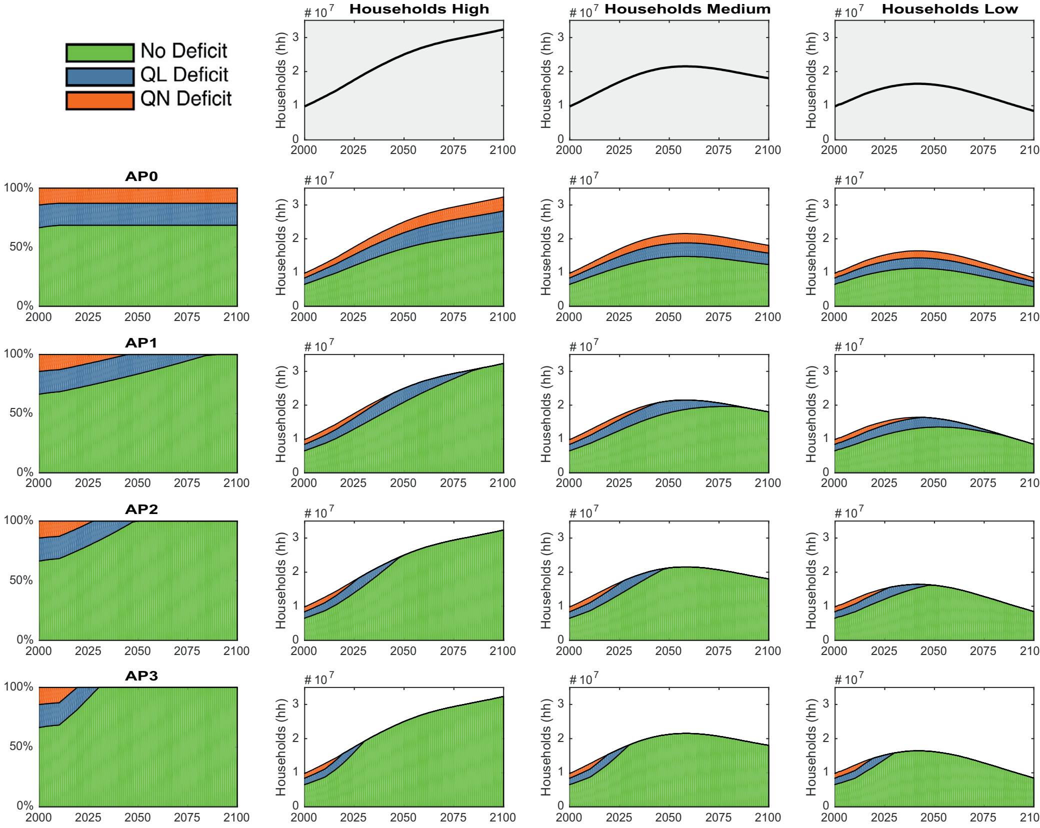


Fig. 3. Household stock by type (green: ND, blue: QL, orange: QN), 2000–2100. Results for the twelve scenarios: combinations of three household series (Households High, Medium and Low defined in Table 1) and four alternative deficit distribution paths (AP0, AP1, AP2 and AP3).

When comparing other alternative deficit paths, AP3, which closes quantitative deficits by 2020 and qualitative deficits by 2030, exhibits more pronounced changes in stock composition. Conversely, deficit path AP1 effects slower changes in stock composition (see Fig. 5b and Fig. S4.2).

The results for the constant-deficit path (AP0) imply that, besides adequate (ND) dwellings, during the period 2016–2100, between 1 and 4 million dwellings inappropriate for living (QN) and between 0.9 and 5.4 millions of dwellings without minimum services (QL) are built (see Fig. 6). Inadequate dwellings are built because social and economic conditions do not improve in AP0, which limits access to non-deficient but costlier dwellings.

Depending on the households and deficit path assumptions, the total 2016–2100 number of new adequate dwellings and renovated dwellings required to close housing gaps lies between 3.6 and 7.4 million. Additionally, between 3.1 and 27.2 million new dwellings are needed in the same period in order to meet increased housing needs of the “no deficit” population, and/or to replace demolished

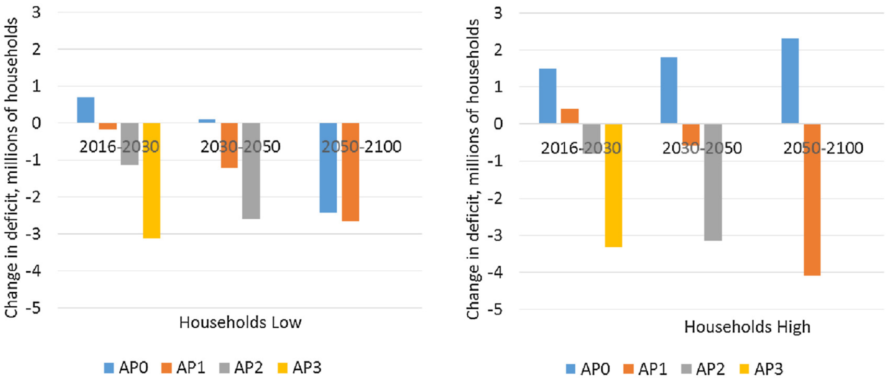


Fig. 4. Changes in households in deficit for the Households Low (left)/High (right) scenarios.

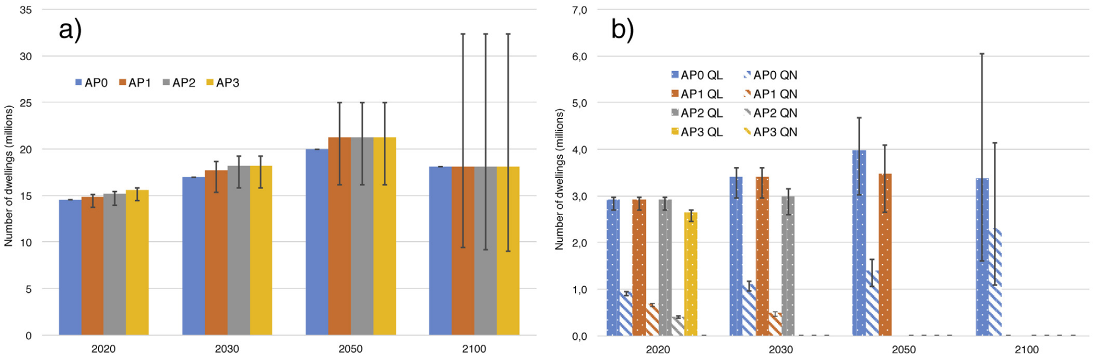


Fig. 5. Dwelling stock, a) total and b) by deficit type QL and QN, by alternative deficit path (blue: AP0, orange: AP1, gray: AP2, yellow: AP3) for the Household Medium series in the years 2020, 2030, 2050 and 2100. The uncertainty bars depict variations in results given by the Households High (upper limit) and Households Low (lower limit) series.

ND dwellings that reached the end of their useful life. The large variability in the last results mainly obeys the differences in the households forecast (see Fig. 6).

Table 4 summarizes the cumulative 2016–2100 construction activities needed to close housing deficits. The construction required to sustain the needs of the ND households is excluded from the table. To eliminate housing deficits by 2030 the AP3 path requires building between 0.79 and 0.85 million new dwellings and upgrading between 2.8 and 3.28 dwellings. By contrast, closing housing deficits by 2090 (AP1) requires to build between 1.72 and 2.13 million dwellings and upgrading between 2.2 and 5.21 million existing dwellings. Yet, to maintain the ND stock after 2030, the construction activity of ND dwellings is higher in AP3 than in AP2 and AP1.

Achieving deficit reduction goals implies a significant increase in construction activity of adequate (ND) dwellings. As Table 5 shows, between 23 thousand (AP3) and 62 thousand (AP1) new dwellings per year need to be built in order to close quantitative housing gaps by 2050. These figures are a considerable increase over the average of 140 thousand total new dwellings built per year reported by the Colombian Builders Association (Camacol, 2010).

Unlike construction dynamics, whose pattern and magnitude vary across dwelling types, deficit paths and households' projections (see Fig. 6), demolitions show a similar behavior in all scenarios (see Fig. 7). This is reflected in the forecasted cumulative demolition for the period 2016–2100 which ranges between 8.9 and 10.2 million dwelling across scenarios, with demolition rates expected to increase from 27 thousand dwellings per year in 2016 to 230 thousand dwellings per year in 2100 (11.7% growth).

The dominant demolition trend, as Fig. 7 shows, is of continuous growth in activity during the rest of the 21 st century, with a growth rate that is more pronounced after 2050, and that tends to slow down towards 2100. This demolition pattern is a delayed outflow of past construction activity, particularly of the expansion in dwelling stock observed after 1950 when population increased rapidly and household size began to decrease.

The only effect of closing housing deficits on demolition activity is a temporary increase in the planned demolition of vacant inadequate dwellings (QN), which lasts until the quantitative deficit is closed. Then, as observed in Fig. 7, planned demolition takes place between 2016 and the years 2020, 2030 and 2045 for AP3, AP2 and AP1 respectively. The resulting average cumulative planned demolitions (as in the Household Medium scenarios) is approximately 577 thousand, 668 thousand and 711 thousand dwellings for AP1, AP2 and AP3 respectively. Planned demolitions vary between 6 and 96 thousand dwellings per year across scenarios (see Fig. 7). Demographic decline, instead of flows of households from quantitative deficit to no deficit, are the cause of vacancies in AP0-Households low scenario.

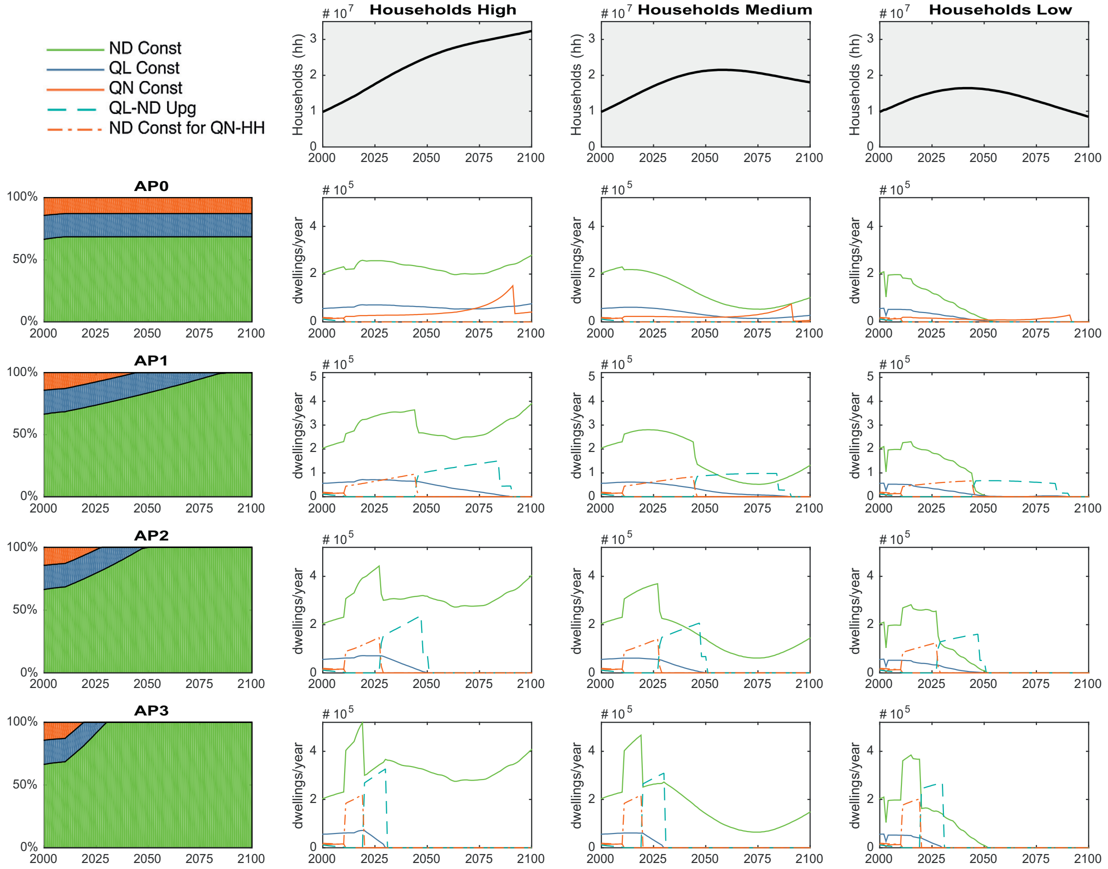


Fig. 6. Constructions and upgrades by type of dwellings, number of dwellings 2000–2100. Results for the twelve scenarios: combinations of three household series (Households High, Medium and Low) and four alternative deficit distribution paths (AP0, AP1, AP2 and AP3). The series "ND Const for QN-HH" represents the fraction of ND dwellings constructed for closing the Quantitative Deficit QN.

Table 4
Building activity required to close deficits: total dwellings built and upgraded between 2016 and 2100 (million).

			Alternative deficit path			
			AP0	AP1	AP2	AP3
Target year for closing deficit	quantitative, QN		–	2045	2030	2020
	qualitative, QL		–	2090	2050	2030
Dwellings for closing deficit 2016–2100 (million)	Households High	New	–	2.13	1.53	0.85
		Upgrade	–	5.21	4.08	3.28
		Total	–	7.35	5.60	4.13
	Households Medium	New	–	2.00	1.49	0.85
		Upgrade	–	3.91	3.69	3.16
		Total	–	5.91	5.18	4.01
	Households Low	New	–	1.72	1.36	0.79
		Upgrade	–	2.62	3.03	2.83
		Total	–	4.35	4.39	3.63
2100 remaining deficit, million households, all demographic scenarios	QN		1.6–6.4	0	0	0
	QL		1.08–4.1	0	0	0

5. Discussion and conclusions

5.1. Method and results: strengths, limitations and uncertainty

We propose a novel modeling approach for studying housing stocks with housing deficits. Our approach expands on the socio-demographic dimension of current dynamic stock models in the field of Material Flow Analysis (MFA) by differentiating across household types that represent distinct dwelling conditions. The dwelling stock is complemented with a household stock of different types, which allows to estimate unsatisfied housing needs

Table 5
Average construction of new additional and upgraded dwellings per year for closing deficits in the periods 2016–2049 and 2050–2100, selected scenarios.

Number of households	Period	Average construction rate, dwellings per year					
		AP1		AP2		AP3	
		New	Upgrade	New	Upgrade	New	Upgrade
High	2016–2049	62772	13797	44934	117529	25061	96485
	2050–2100	0	93011	0	1566	0	0
Medium	2016–2049	58829	11949	43876	106606	24866	93077
	2050–2100	0	68621	0	1332	0	0
Low	2016–2049	50671	9263	40068	87623	23311	83361
	2050–2100	0	45269	0	1012	0	0

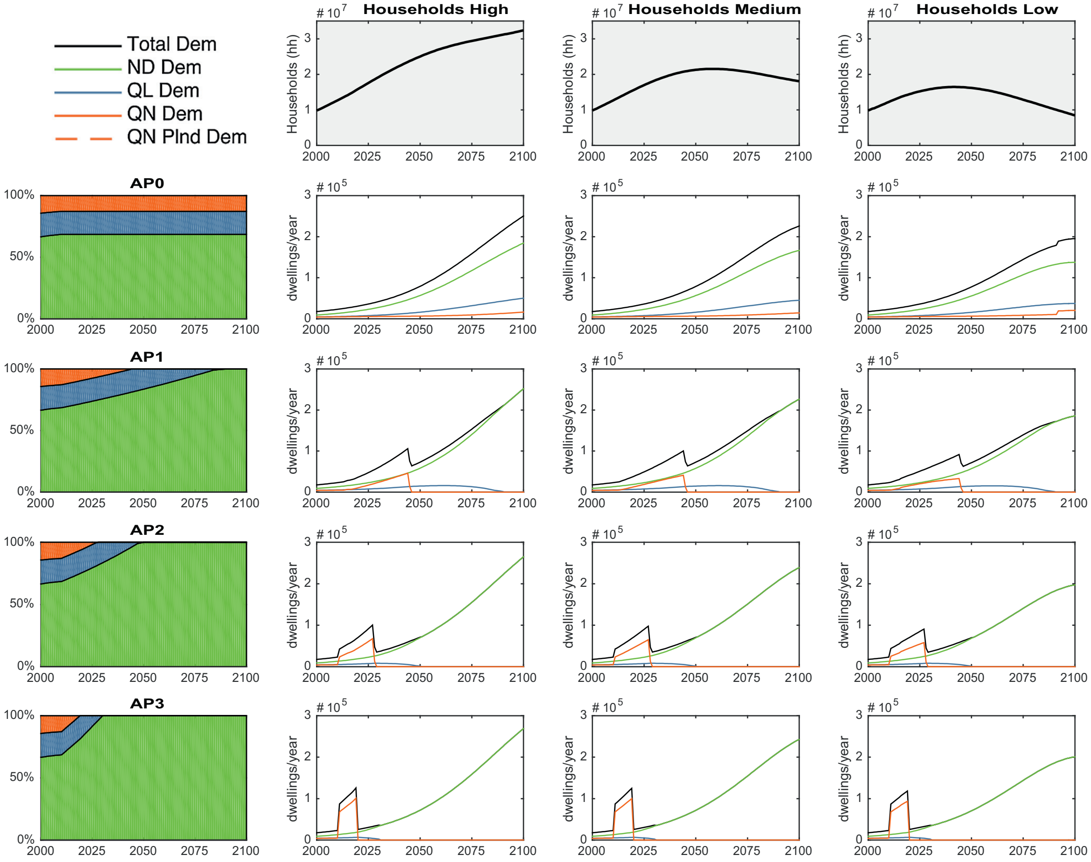


Fig. 7. Demolitions by type of dwelling (black: Total, green: ND, blue: QL, orange: QN), number of dwellings 2000–2100. Results for the twelve scenarios: combinations of three household series (Households High, Medium and Low) and four alternative deficit distribution paths (AP0, AP1, AP2 and AP3).

and to evaluate different strategies for closing deficits in terms of construction and demolition activity.

Housing deficits are the result of complex economic and social phenomena. The method we propose takes these phenomena as exogenous, and explores different paths for closing deficits that assume that policies are effectively implemented. Thus, our results rest on the premises that housing policies (i) properly address physical deficiencies of housing by building and upgrading dwellings, (ii) control other economic and social causes of housing deficits, and (iii) are sustained over time, meaning that economic and social conditions do not worsen, and no households move from the no deficit to the deficit states. The latter also means that QL and QN dwellings are replaced when needed but also demolished when in excess. These are strong assumptions, but allow to assess the magnitude of the housing deficits and the efforts needed to close them. In this sense, our results constitute a benchmark against which policy options, including one-shot measures, can be tested and compared.

Of the demographic factors considered in this study, household size is least studied and most uncertain. We assumed that household size in Colombia will follow the declining trends observed in developing countries since the 1600s, which are explained by declining fertility rates and a move from complex, extended, family structures to nuclear families (Bongaarts, 2001; Bradbury et al., 2014; Keilman, 1987). Although developing countries show a less consistent trend in household size than developed ones (Bongaarts, 2001), our assumption is supported by observations in Latin America and the Caribbean, where lower fertility caused a decline in average household size from 5.25 in the 1970s to 4.7 in 1990s (CEPAL, 1995). As one of the factors determining future demands for housing and resources, a more detailed study of household size trends is needed in order to understand the long-term implications of changing demographics on resource use in Colombia. The number of households, however, is more sensitive to population growth than to household size which means that results are consistent for variations in the latter.

The relationship of number of households to number of dwellings is also subject to uncertainty. The parameter households per dwelling is likely to be overestimated for the no deficit (ND) type, leading to an underestimation of the number of dwellings in this share of the stock. Although there are no statistics on the number of households in Colombia with a second (not for rent) home, we expect this number to be below the 5–6% observed in the U.S. in 2001 (Simmons and O'Neill, 2001) and the U.K. in 2014 (Office for National Statistics, 2015), respectively, based on the fact that income inequality is greater in Colombia than in developed countries (World Bank, 2016). Then, not all of the 547 thousand households in the top 5% of income in Colombia (DANE, 2015) can afford a second house.

The uncertainty in construction and demolition and its impact on the dwelling stock was not addressed/explored and our historical construction and demolition results were not validated due to the lack of available statistics. This, in combination with the non-existent information on the lifetime of dwellings causes dwelling stock results to be uncertain. Notwithstanding, the model's results correctly represent the evolution of household stock and therefore, the conclusions about the number of dwellings needed to close housing deficits are valid.

5.2. Policy

Housing needs in developing countries are expected to increase continuously during most of the XXI century, even if population declines. This is because during the development process there are other expected socioeconomic and lifestyle changes that decrease the average number of persons per households, as observed in already-developed nations. In this regard, results in AP1 do not intend to reflect a policy but to aid decision making by illustrating that, to reduce deficits, housing policies need to be more aggressive.

Policies for closing housing deficits need to be based on knowledge of demographic and stock development and their links. Although demographic decline can reduce the number of households with deficit and the construction efforts for closing housing deficits in the long term, particularly after 2050, results show that deficit is not closed unless measures are adopted. Conversely, regardless of the demographic scenario, delaying actions increases the total number of new and upgraded dwellings required to close the gap.

More than 23 thousand additional dwellings need to be built each year in order to close quantitative housing deficit by 2020, and more than 80 thousand dwellings per year are to be upgraded to close qualitative deficit by 2030. Achieving this 7 to 22% increase in construction with respect to the status quo (AP0) requires a significant amount of resources, particularly land, whose availability is constrained in main urban areas (Camacol, 2010). In addition, conditions vary widely across regions and cities. Since municipalities have responsibility to regulate land use and implementing housing policies, municipalities where action is most urgent have a much larger challenge than the national average. A spatially disaggregated approach could assist in identifying critical areas and designing housing policies.

Our estimation of the effort needed to close housing deficits is consistent with Gilbert's (2014) assessment that it would take at least 12 years to close deficits assuming that current radical policies are successfully implemented and sustained, and that housing demand stays constant. If no actions are taken to close housing deficit, construction activity is not expected to grow in the next two decades. If the deficit distribution remains at present levels, the construction activity would remain constant or even decline for the rest of the century.

If policies for closing deficits are implemented, the future annual construction activity is expected to increase. The magnitude of construction growth depends on the path and time horizon defined for closing deficits.

Most demolitions are caused by the obsolescence of dwelling stock and, during the 21st century, demolitions are largely independent of housing policies and demographic changes. Actions for closing deficit marginally increase cumulative demolitions by increasing planned demolitions of QN dwellings. Although the impact of polices on the demolition activity of QN dwellings (the dominant type of demolition) is low, closing quantitative deficits can potentially increase the expected short-term annual demolitions by a factor up to six. Then, planned demolitions need to be accompanied by plans to manage demolition waste.

Delaying actions to close deficit causes a decrease in planned QN demolitions but, as discussed before, it also increases the number of households in deficit (except in the Households Low scenarios). Furthermore, these actions will result in longer and postponed planned-demolitions periods. These results emphasize the need for understanding the long-term dynamics of dwelling and household stocks as well as their interactions.

Addressing current housing needs is urgent for having a more equitable and sustainable society. Regardless of demographic changes, our results show that the sooner housing deficits are closed, the fewer resources are needed in order to achieve deficit-reduction goals. In addition, as employment and construction are closely related (Clavijo et al., 2004), an accelerated program to close housing deficits contributes to stimulating economic growth through multiplier effects. For this paper we assume that quantitative deficits are closed before qualitative deficits, but this needs not to be a constraint for policy design and both types of deficits can be simultaneously targeted.

Conflicts might appear when reconciling economic and housing deficit policies, as sustaining long periods of large construction might be economically beneficial in term of materials flows and employment but these might compromise environmental goals on land use, materials, energy efficiency and emissions.

Acknowledgements

The authors would like to thank the reviewers for their valuable comments which greatly contributed to the improvement of the manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2016.09.028.

References

Bergsdal, H., Brattebø, H., Bohne, R.A., Müller, D.B., 2007. Dynamic material flow analysis for Norway's dwelling stock. Build. Res. Inf. 35, 557–570, http://dx.doi.org/10.1080/09613210701287588.

Bongaarts, J., 2001. Household size and composition in the developing world in the 1990. Popul. Stud. (N.Y.) 55, 263–279, http://dx.doi.org/10.1080/00324720127697.

Bouillon, C.P., Azevedo, V., Medellín, N., Boruchowicz, C., 2012a. ¿Dos habitaciones, dos baños y un patio grande? La demanda de vivienda en América Latina y el Caribe. In: Bouillon, C.P. (Ed.), Un Espacio Para El Desarrollo: Los Mercados De Vivienda En América Latina Y El Caribe. Banco Interamericano de Desarrollo, Washington, D.C (p. 385).

Bouillon, C.P., Medellín, N., Boruchowicz, C., 2012b. Retrato de un problema: el sector de la vivienda. In: Bouillon, C.P. (Ed.), Un Espacio Para El Desarrollo. Los Mercados De Vivienda En América Latina Y El Caribe. Banco Interamericano de Desarrollo, Washington, D.C, p. 385.

Bradbury, M., Peterson, M.N., Liu, J., 2014. Long term dynamics of house hold size and their environmental implications. Popul. Environ. 36, 73–84, http://dx.doi.org/10.1007/s11111-014-0203-6.

CENAC, n.d. Evolución del Déficit Habitacional en Colombia. 1993–2005. Bogotá, D.C.

CEPAL, 1995. Alojar para el desarrollo: una tarea para los asentamientos humanos., in: Reunión Regional de América Latina Y El Caribe Preparatoria de Hábitat II Santiago de Chile.

Camacol, 2010. La vivienda 2011–2014: El gran salto en la producción habitacional. Inf. Económico, 9.

Clavijo, S., Janna, M., Muñoz, S., 2004. La vivienda en Colombia: Sus Determinantes Socio-Económicos y Financieros. Bogotá, D.C.

Cohen, B., 2004. Urban growth in developing countries: a review of current trends and a caution regarding existing forecasts. World Dev. 32, 23–51, http://dx.doi.org/10.1016/j.worlddev.2003.04.008.

Congreso de Colombia, 2012. Ley 1537 20 Jun 2012. Por la cual se dictan normas tendientes a facilitar y promover el desarrollo urbano y el acceso a la vivienda y se dictan otras disposiciones. Colombia.

DANE, 2005. CENSO GENERAL 2005 [WWW Document] Población Y Demogr., URL http://www.dane.gov.co/index.php/poblacion-y-registros-vitales/censos/censo-2005 (accessed 6.20.02.).

DANE 2008 Censo general 2005 Ficha Metodológica Déficit de Vivienda Bogotá, D.C.

DANE, 2015. Pobreza Monetaria Y Multidimensional [WWW Document] Estadísticas Soc. Pobr. Y Desigual, URL http://www.dane.gov.co/index.php/estadisticas-sociales/pobreza (accessed 2.1.16.).

Dane, 2016. Empleo Informal Y Seguridad Social [WWW Document] Gran Encuesta Integr. Hogares, URL http://www.dane.gov.co/index.php/estadisticas-por-tema/mercado-laboral/empleo-informal-y-seguridad-social (accessed 8.20.16.).

Denmark, S., 2013. Denmark in Figs 2013. Copenhagen.

Fique Pinto, L.F., 2008. La política pública de vivienda en Colombia. Conflicto de objetivos. Bitacora 13, 73–89.

Gallardo, C., Sandberg, N.H., Brattebø, H., 2014. Dynamic-MFA examination of Chilean housing stock: long-term changes and earthquake damage. Build. Res. Inf., 1–16, http://dx.doi.org/10.1080/09613218.2014.872547.

Gilbert, A., 2001. Housing in Latin Amreica (No I-7UE). INDES –EUROPEAN UNION JOINT PROGRAM WORKING PAPERS, Washington, D.C.

Gilbert, A.G., 2014. Free housing for the poor: an effective way to address poverty? Habitat Int. 41, 253–261, http://dx.doi.org/10.1016/j.habitatint.2013.08.009.

Hu, M., Bergsdal, H., van der Voet, E., Huppes, G., Müller, D.B., 2010a. Dynamics of urban and rural housing stocks in China. Build. Res. Inf. 38, 301–317, http://dx.doi.org/10.1080/09613211003729988.

Hu, M., Pauliuk, S., Wang, T., Huppes, G., van der Voet, E., Müller, D.B., 2010b. Iron and steel in Chinese residential buildings: a dynamic analysis. Resour. Conserv. Recycl. 54, 591–600, http://dx.doi.org/10.1016/j.resconrec.2009.10.016.

Hu, M., Van Der Voet, E., Huppes, G., 2010c. Dynamic material flow analysis for strategic construction and demolition waste management in beijing. J. Ind. Ecol. 14, 440–456, http://dx.doi.org/10.1111/j.1530-9290.2010.00245.x.

Huang, T., Shi, F., Tanikawa, H., Fei, J., Han, J., 2013. Materials demand and environmental impact of buildings construction and demolition in China based on dynamic material flow analysis. Resour. Conserv. Recycl. 72, 91–101, http://dx.doi.org/10.1016/j.resconrec.2012.12.013.

Intergovernmental Panel on Climate Change, 2014. Climate Change 2014 Mitigation of Climate Change, Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, http://dx.doi.org/10.1017/CBO9781107415416.

Kavgic, M., Mavrogianni, a., Mumovic, D., Summerfield, a., Stevanovic, Z., Djurovic-Petrovic, M., 2010. A review of bottom-up building stock models for energy consumption in the residential sector. Build. Environ. 45, 1683–1697, http://dx.doi.org/10.1016/j.buildenv.2010.01.021.

Keilman, N., 1987. Recent trends in family and household composition. Eur. J. Popul. 3, 297–325.

Kohler, N., Hassler, U., 2002. The building stock as a research object. Build. Res. Inf. 30, 226–236, http://dx.doi.org/10.1080/09613210110102238.

Lucon, O., Ürge-Vorsatz, D., Zain Ahmed, A., Akbari, H., Bertoldi, P., Cabeza, L.F., Eyre, N., Gadgil, A., Harvey, L.D.D., Jiang, Y., Liphoto, E., Mirasgedis, S., Murakami, S., Parikh, J., Pyke, C., Vilariño, M.V., 2014. Buildings. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, USA.

Müller, D.B., 2006. Stock dynamics for forecasting material flows—Case study for housing in The Netherlands. Ecol. Econ. 59, 142–156, http://dx.doi.org/10.1016/j.ecolecon.2005.09.025.

Monkkonen, P., 2013. Housing deficits as a frame for housing policy: demographic change, economic crisis and household formation in Indonesia. Int. J. Hous. Policy 13, 247–267, http://dx.doi.org/10.1080/14616718.2013.793518.

Murcia Pabón, A., 2007. Determinante del acceso al crédito de los hogares colombianos. Borradores Econ. 449, Murcia Pabón, A. (2007). Determinante del acceso a.

Murray, C., Clapham, D., 2015. Housing policies in Latin America: overview of the four largest economies. Int. J. Hous. Policy 15, 347–364, http://dx.doi.org/10.1080/14616718.2015.1055090.

ONU-Habitat, 2012. Hábitat y Desarrollo Humano. Programa de las Naciones Unidas para el Desarrollo, Programa de las Naciones Unidas para los Asentamientos Humanos-UN Hábitat y Centro de Estudios de la Construcción y el Desarrollo Urbano Regional.

ONU-Habitat, 2015. Déficit habitacional en América Latina y el Caribe: una herramienta para el diagnóstico y el desarrollo de políticas efectivas en vivienda y hábitat. Nairobi.

Office for National Statistics, 2015. Percentage of Households in the UK with a Second Dwelling, by Tenure, 2014 [WWW Document], URL https://www.ons.gov.uk/peoplepopulationandcommunity/housing/adhocs/005105percentageofhouseholdsintheukwithaseconddwellingbytenure2014 (accessed 3.30.16.).

Ortiz I., Cummins M., 2011. WORKING PAPER GLOBAL INEQUALITY: BEYOND THE BOTTOM BILLION A Rapid Review of Income Distribution in 141 Countries.

Pauliuk, S., Sjöstrand, K., Müller, D.B., 2013. Transforming the norwegian dwelling stock to reach the 2 degrees celsius climate target. J. Ind. Ecol. 17, 542–554, http://dx.doi.org/10.1111/j.1530-9290.2012.00571.x.

Sandberg, N.H., Brattebø, H., 2012. Analysis of energy and carbon flows in the future Norwegian dwelling stock. Build. Res. Inf. 40, 123–139, http://dx.doi.org/10.1080/09613218.2012.655071.

Sandberg, N.H., Bergsdal, H., Brattebø, H., 2011. Historical energy analysis of the Norwegian dwelling stock. Build. Res. Inf. 39, 1–15, http://dx.doi.org/10.1080/09613218.2010.528186.

Sandberg, N.H., Sartori, I., Brattebø, H., 2014a. Using a dynamic segmented model to examine future renovation activities in the Norwegian dwelling stock. Energy Build. 82, 287–295, http://dx.doi.org/10.1016/j.enbuild.2014.07.005.

Sandberg, N.H., Sartori, I., Brattebø, H., 2014b. 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. 85, 136–144, http://dx.doi.org/10.1016/j.enbuild.2014.09.028.

Sartori, I., Bergsdal, H., Müller, D.B., Brattebø, H., 2008. Towards modelling of construction, renovation and demolition activities Norway's dwelling stock, 1900–2100. Build. Res. Inf. 36, 412–425.

Sartori, I., Wachenfeldt, B.J., Hestnes, A.G., 2009. Energy demand in the Norwegian building stock: scenarios on potential reduction. Energy Policy 37, 1614–1627, http://dx.doi.org/10.1016/j.enpol.2008.12.031.

Schiller, G., 2007. Urban infrastructure: challenges for resource efficiency in the building stock. Build. Res. Inf. 35, 399–411, http://dx.doi.org/10.1080/09613210701217171.

Seto, K.C., Dhakal, S., Bigio, A., Blanco, H., Delgado, G.C., Dewar, D., Huang, L., Inaba, A., Kansal, A., Lwasa, S., McMahon, J.E., Müller, D.B., Murakami, J., Nagendra, H., Ramaswami, A., 2014. Human settlements, infrastructure and spatial planning. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, USA.

Simmons, T., O'Neill, G., 2001. Households and Families: 2000.

Statista, 2016. Urban Population Living in Slums by Region 2000–2014 | Statistics [WWW Document], URL http://www.statista.com/statistics/295528/urban-population-living-in-slums-by-region/(accessed 3.24.16.).

Swan, L.G., Ugursal, V.I., 2009. Modeling of end-use energy consumption in the residential sector: a review of modeling techniques. Renew. Sustain. Energy Rev. 13, 1819–1835, http://dx.doi.org/10.1016/j.rser.2008.09.033.

UN-Habitat, 2003. THE CHALLENGE OF SLUMS: Global Report on Human Settlements 2003, 1st ed. United Nations Human Settlements Programme (UN-Habitat), Nairobi, Kenia.

UN-Habitat, 2012a. Prosperity of cities: state of the world's cities 2012/2013. State of the World's Cities., http://dx.doi.org/10.1080/07293682.2013.861498.

UN-Habitat, 2012b. Sustainable Housing for Sustainable Cities: A Policy Framework for Developing Countries. United Nations Human Settlements Program, Nairobi.

UNSD, U.N.S.D, 2015. Slum Population as Percentage of Urban, Percentage [WWW Document] Millenium Dev. Goals Indic. URL http://mdgs.un.org/unsd/mdg/seriesdetail.aspx?srid=710.

United Nations, 1974. Compendium of Housing Statistics 1971. Department of Economic and Social Affairs. Statistical Office, NewYork.

United Nations, 1980. Compendium of Housing Statistics 1975–1977, third. ed. Department of International Economic and Social Affairs. Statistical Office, New York.

United Nations, 2014. Households and Families [WWW Document] Demogr. Soc. Stat., URL http://unstats.un.org/unsd/demographic/sconcerns/fam/fammethods.htm (accessed 9.1.15.).

United Nations, 2015. Probabilistic Population Projections based on the World Population Prospects: The 2015 Revision.

Ürge-Vorsatz D., Eyre N., Graham P., Harvey D., Hertwich E., Jiang Y., Kornevall C., Majumdar M., McMahon J.E., Mirasgedis S., Murakami S., Novikova A., 2012. Chapter 10 – Energy End-Use: Building, in: Global Energy Assessment – Toward a Sustainable Future. Cambridge University Press Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 649–760.

Vásquez, F., Løvik, A.N., Sandberg, N.H., Müller, D.B., 2016. Dynamic type-cohort-time approach for the analysis of energy reductions strategies in the building stock. Energy Build. 111, 37–55, http://dx.doi.org/10.1016/j.enbuild.2015.11.018.

World Bank, 2016. GINI Index (World Bank Estimate) [WWW Document] World Dev. Indic., URL http://data.worldbank.org/indicator/SI.POV.GINI/countries?display=map (accessed 4.14.16.).

Paper 3

Food security for an ageing and heavier population.

Vásquez, F., Vita, G., and Müller, D.B. (submitted).

Food security for an ageing and heavier population

Felipe Vásquez [†,*], *Gibran Vita* [†], *Daniel B. Müller* [†]

[†] Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway.

ABSTRACT

Population growth, dietary shifts, and food waste are commonly assumed as the main drivers for increased food demand. Although nutrition sciences demonstrate that biophysical characteristics determine food requirements on individuals, and demographic studies provide evidence for large shifts in height, weight and age structure worldwide, the aggregated effects are poorly understood. Here, we analyze the effects of these changes in the adult population of 186 countries between 1975 and 2014. Across countries, individuals' weight gains ranged between 6% and 33% and energy needs increased between 0.9% and 16%. Globally, food energy increased 129%. Population growth contributed 116%, weight and height gains 15%, while the aging phenomenon counteracted the rise in energy needs by 2%. This additional 13% demand corresponded to the needs of 286 million adults. We show that bridging the understanding of the evolving individual-biophysical and sociodemographic characteristics can contribute to better global resource and food security assessments.

1. INTRODUCTION

Human activity is regarded as the dominant cause of contemporary environmental change[1–4]. The most comprehensive assessments to understand the human-environment relationship traditionally describe resource use as a function of the population size, affluence and technology[4–10]. Yet, population remains as an external variable, deprived of evolving biophysical traits. Evidence shows that humans changed at the individual and societal levels over the past century. Height[11], body mass index[12,13] (BMI) and longevity[14] have all increased while demographic transitions have occurred due to an ageing population and changes in fertility and mortality rates[15,16]. Still, the effects of individual and societal changes on resource use have been overlooked and are therefore poorly understood.

This is particularly important for food demand, which is not solely dependent on economic and technological factors but ultimately is a function of the energetic metabolic requirements of humans[17]; which depend on sex, age, weight, and physical activity level. The influence of these factors has been studied in individuals[18–20] and to a lesser extent at societal levels[21–23]. Furthermore, most studies concerned with global food security overlook the effect of changes in the metabolic requirements of humans[24–28], and mainly focus on the technological aspects of food losses and waste [29,30].

To our knowledge, there are two studies that evaluate the food energy issue from a metabolic perspective at the global scale. Walpole et al.[22] studied the adult population of 190 countries for the year 2005. Their results focus on the impact of overweight and obesity and show that the energy requirements due to these factors corresponds to 135 million average adults. They also conclude that increasing overweight and obesity could have the effect of an extra half a billion people by 2050.

More recently, Hiç et al.[23] studied the energy requirements for 169 countries from a longitudinal perspective (1950-2050), including infants, children, adolescents, adults, elders, and pregnant and lactating women. The authors found that the average population's energy requirements increased in the past by 2.2% due to demographic structural changes, while using static average weight values. Despite this study capturing most of the nuances of the human food requirements, it disregards the biophysical changes in height and BMI which are proven to be relevant factors for explaining changes in food demand. Thus, longitudinal food energy studies that account for these changes at the global scale are missing.

In this article, we present the integrated effect of individual biophysical - height and BMI - and demographic changes on the human mass and food energy requirements of the adult population of 186 countries from 1975 to 2014. Our estimates are based on yearly sex-and-age disaggregated data for each country which comprise 114 birth cohorts. The results are presented at the aggregated level.

2. MATERIALS AND METHODS

We estimate long-term food energy requirements and weight following a "type-cohort-time" approach for modelling energy in dynamic stocks[31,32]. Here, we regard population as a stock constituted of individual humans of different sexes (types) and cohorts, whose biophysical characteristics and energy needs evolve in time.

We apply the FAO guidelines[17] for total human energy expenditure to approximate daily **food energy** demand. First, we calculate the basal metabolic rate (BMR) as a function of weight, sex and age with the guide's formulae on "Table 5.2". Then, we estimate the average food energy need (theoretical energy expenditure) by multiplying the BMR by a factor of 1.76 to account for the physical activity level (PAL). This is the average value in FAO's guide (Table 5.1), which represents an "active or moderately active" lifestyle. We assume it to be the same for all population because PAL information is not available for most of the countries.

We follow Walpole's[22] considerations to derive **weight** from BMI and height [Weight = BMI x Height^2]. BMI and height are taken from studies from the NCD Risk Factor Collaboration[11,13].

We assume that the annual information on mean **BMI**, only available by sex, is representative for adults of all ages. This allows the sex-cohort-time average weight calculations. In addition, we deem the mean adult **height**, reported at the age of 21, to be achieved at the age of 18 for consistency with the BMI data - which reports from this age. Height data is available for the 1896-1996 cohorts, hence adults from the 1875-1895 cohorts are considered to have the same height as their 1896 peers. The assumptions on height have a minor effect in the results and conclusions, as the population in the cohorts of concern represent a small share of the total adult population.

Average (per capita) values of food energy and weight at the national and global levels are weighted-averages by population size, sex and age. The **total food energy** requirements and the **total mass** (of a nation) aggregates weight and energy demand of the individuals of all ages and sexes.

We use the **population** statistics from the United Nations[33], which are available for every year of analysis by age-groups of 5 years. For the 1975-1989 period, the data is available for 17 age-groups covering the ages 0 to 80+. For the 1990-2014 period, the data is available for 21 age-groups for the ages 0 to 100+. For every year of analysis, we distribute the age-group's population equally among each individual age of the group. For the period 1975-1989 we apportion the 80+ population among the ages 80 to 100+ by using the distribution of 1990.

3. RESULTS AND DISCUSSION

Global Trends. In the past four decades, the adult population increased by 116%. Yet, population change was outgrown by increases of 146% in human mass and 129% in total theoretical food energy requirements (Figure 1a). In 2014, the adult population was 4.98 billion people, weighted 322 Mton, and demanded 13 Tkcal/day (Figure S1). Five countries contained half of the adult population - China, India, United States, Indonesia, and Brazil -, which along with Russia also concentrated 50% of the human mass and food energy requirements.

In 2014, the average world adult weighed 64.7 kg, was 163 cm tall and 42 years old, and demanded 2615 kcal/day - assuming an active or moderately active lifestyle[17] (Figure 2). This is 14% heavier, 1.3% taller, 6.2% older, and 6.1% more energy demanding than the average adult in 1975 (Figure 1b and Figure 2). From a global perspective, the effect of this additional demand is equivalent to the food energy needs of 286 million adults today - about 1.2 times the adult population of United States, or the double of Brazil. The total mass increase due to additional weight was 39.68 Mton, almost the adult mass of India or two times that one of United States.

Population, human mass and food energy grew similarly but at different rates (Figure 1c). The non-linear relationship between weight and food energy changes (Figure S2b) explains the continuous decoupling between weight gains and energy increases (Figure 1b). The food energy demand per kilogram weight (energy-to mass ratio) decreased by almost 7%, from 43.4 to 40.4 kcal/kg. For every kilogram increase there was a reduction of 70 to 91 calories needed per kilogram-weight.

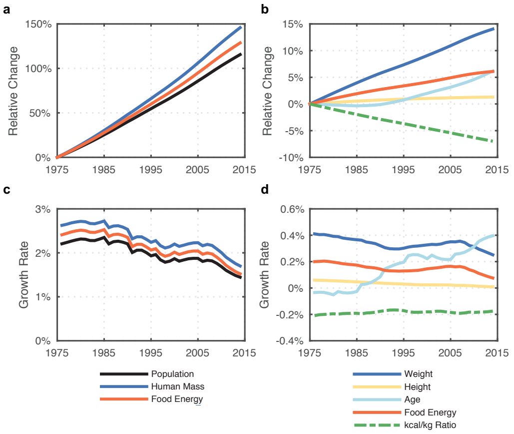


Figure 1. Relative changes (a,b) and growth rates (c,d) in population, human mass, and food energy (a,c) and weight, height, age, food energy and energy-to-mass ratio (b,d) with respect to 1975. While human mass refers here to the total population, the term weight is used to indicate the average mass per capita.

The total mass and energy growth rates declined between 1986-1998 and 2006-2014, mainly following the population trend (Fig. 1c). In addition, these periods were characterized by decelerations in weight gains and accelerations in ageing (Fig. 1d), which intensified the decoupling between weight and energy. Since energy requirements tend to decline in the latter stages of life[17], ageing mitigated the global surge in food requirements (Figure 3 and Figure S2d).

The ageing effect in the period 1975-2014 avoided an additional 1.9% increase in food energy requirements (Figure 3), corresponding to the food needs of approximately 40 million adults i.e. the adults of South Korea. Conversely, the rise in BMI increased the energy requirements by 14% in the same period (Figure 3). This is equivalent to the food needs of approximately 308 million adults, i.e. the adults of Mexico and United States combined.

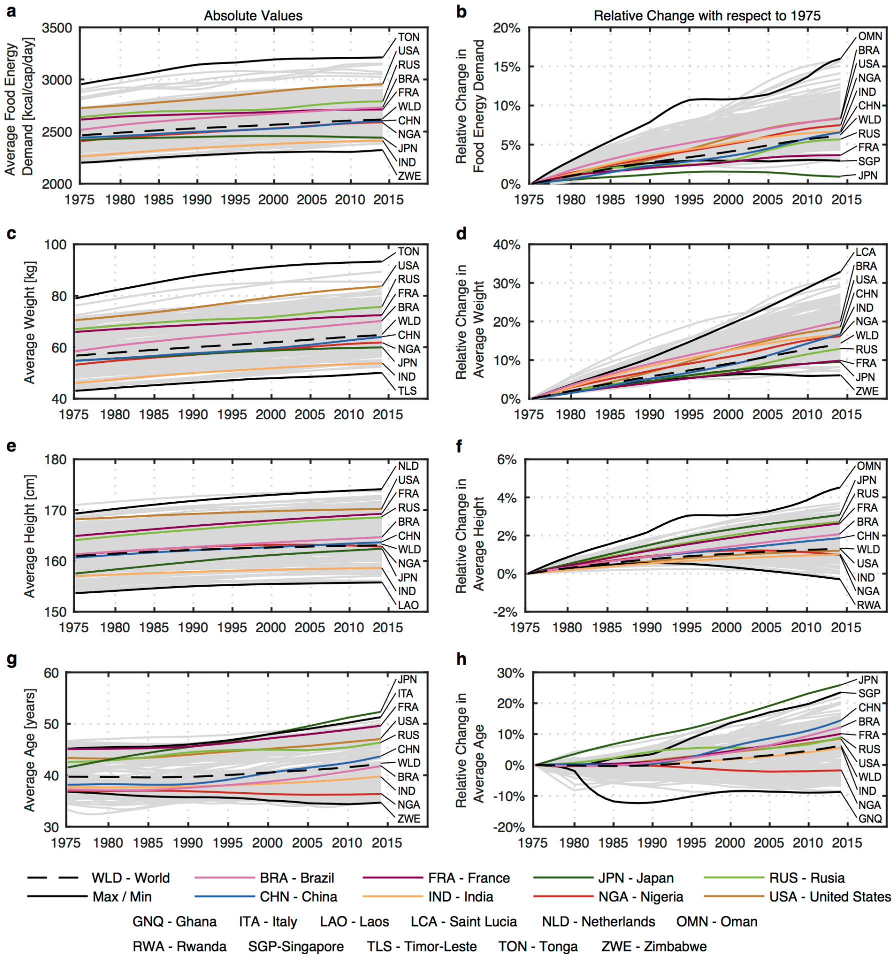


Figure 2. Absolute values (left - a,c,e,g) and relative changes (right - b,d,f,h) in average food energy demand (a,b), weight (c,d), height (e,f) and age (g,h).

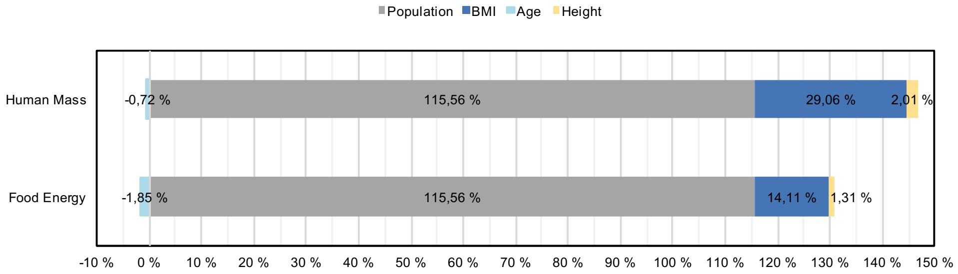


Figure 3. Decomposition analysis of factors contributing to changes in the total human mass and food energy in the period 1975-2014.

Our food energy estimate for the world average adult (2615 kcal/cap/day) are slightly higher than those of Walpole et al.[22] (2549 kcal/cap/day for 2005 adults) and Hiç et al.[23] (2370 kcal/cal/day for all the 2010 population). With respect to Walpole and colleagues our study comprises 9 additional years of weight gains which can explain the difference since our 2005 estimate of 2586 kcal/cap/day is similar to theirs (Dataset S1). The difference with Hiç and colleagues may correspond to the fact that they also include youths which have lower calorie needs.

Hiç et al.[23] report a 2.2% increase in average energy requirements between 1950 and 2010 while our estimates suggest a 6.1% increment between 1975 and 2014. Hiç and colleagues attribute the changes to demographic transitions towards older populations while recognizing the limitations of their approach at not including changes in weight. Our results depict the relevance of considering *both* weight and demographic structural changes when accounting for food energy, and demonstrate that changes in height and BMI had a larger impact than demographics as illustrated in Figure 3.

National Trends. The average adult food energy needs and weight were in the range of 2200-2960 kcal/cap/day and 43-79 kg in 1975 (Figure 2a and 2c). The spectrum moved upwards to 2320-3210 kcal/cap/day and 50-93 kg in 2014 (Figure 4a and 4c). Among countries, absolute gains stretched from 22 to 401 kcal/cap/day and from 4 to 20 kg, with relative fluctuations of 0.9-16% for energy (Figure 2b and 4d) and 6-33% for weight (Figure 2d and 4b).

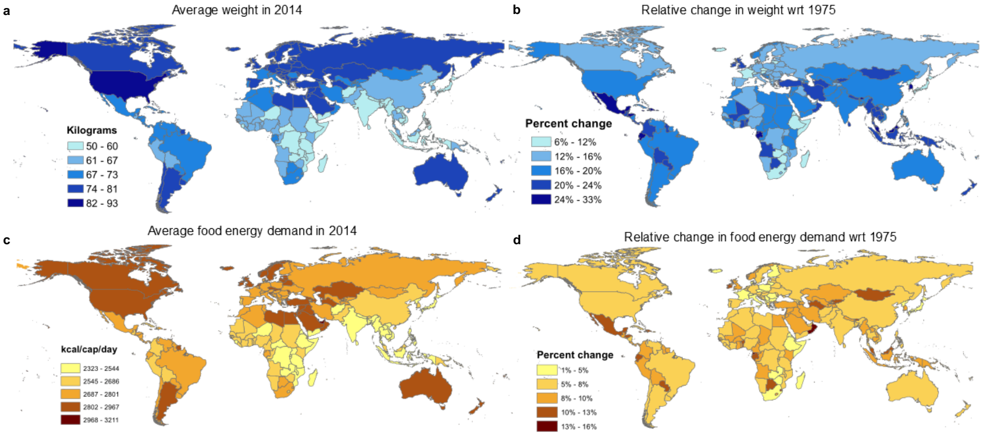


Figure 4. Average weight and food energy needs in 2014 (a,c) and relative change with respect to 1975 (b,d) by country. (a), average weight in kg in 2014, and (b), relative change with respect to 1975 values. (c), average food energy demand in kcal/cap/day in 2014, and (d), relative change with respect to 1975 values.

Notwithstanding this diversity, the disparity between the hungriest and the frugal and between the heaviest and the lightest adults remained nearly constant since 1975. The most demanding country-average adults require about 1.4 more food energy than the most frugal, and the heaviest weigh nearly the double of the lightest (1.86 times).

Higher weight is usually correlated with higher energy demand, however, the countries with the most and least energy demanding adults do not strictly correspond to those with the heaviest and lightest ones (Table 1, and Dataset S1).

In 1975, both the lightest (below 45 kg) and most frugal adults (below 2250 kcal/cap/day) lived in the same countries (Table 1). However, Ethiopia became one of the lightest (below 54 kg) but not one of the most frugal (below 2300 kcal/cap/day) in 2014. In contrast, Nepal remained among those with the lowest energy demand despite a large weight increase (23.7%).

Adults in the Czech Republic, the United States and Iceland were among the heaviest (above 70 kg) but not among the most energy demanding (above 2800 kcal/cap/day) in 1975 (Table 1). Conversely, United Arab Emirates and Qatar had some of the largest energy needs but were not among the heaviest. Moreover, by 2014, Saint Lucia adhered to the heaviest (above 81 kg) but not the most demanding. The countries with the hungriest adults in 1975 remained to be so in 2014.

Also, the relative changes exhibited a remarkable diversity (Table 1). While Zimbabwe and Saint Lucia had the smallest and largest weight gains respectively, Japan and Oman had the smallest and largest energy increases (Figure 2b and 2d).

Table 1 | Highest and lowest average food energy demand and weight.

Average food energy demand [kcal/cap/day]				**Rel. change in food energy 1975-2014**		**Average weight [kg]**				**Rel. change in weight 1975-2014**	
1975		2014				1975		2014			
Highest 10											
TON	2955,8	TON	3211,4	OMN	16,0 %	TON	79,1	TON	93,3	LCA	32,7 %
PYF	2903,5	QAT	3151,3	GNQ	15,7 %	PYF	76,2	WSM	89,3	GNQ	31,1 %
ARE	2879,4	WSM	3143,6	LCA	15,6 %	WSM	72,5	PYF	85,5	CPV	29,4 %
QAT	2831,3	ARE	3070,9	CPV	15,0 %	CZE	71,6	USA	83,6	MDV	28,9 %
KWT	2830,9	PYF	3050,7	GRD	14,1 %	KWT	70,7	LCA	82,7	MYS	27,0 %
WSM	2812,4	KWT	3024,4	VCT	13,4 %	USA	70,6	QAT	81,6	GRD	26,8 %
ISL	2730,7	LCA	2966,8	JAM	12,7 %	ISL	70,1	KWT	80,8	KOR	26,7 %
CZE	2726,8	USA	2953,4	GAB	12,6 %	LTU	69,6	NZL	80,6	JAM	26,3 %
USA	2726,3	PSE	2949,1	KGZ	12,3 %	ARE	68,9	AUS	79,3	VCT	26,2 %
FSM	2707,3	JOR	2941,0	WSM	11,8 %	EST	68,8	IRL	79,2	HND	26,0 %
Lowest 10											
IND	2262,2	JPN	2441,8	CZE	4,4 %	BDI	46,8	ERI	54,9	SGP	10,6 %
BDI	2261,5	LAO	2430,0	MKD	4,3 %	MMR	46,5	NPL	54,8	SOM	10,3 %
MMR	2259,3	KHM	2420,7	MDG	3,7 %	IND	46,1	LAO	54,6	CZE	10,1 %
IDN	2243,8	ETH	2414,8	FRA	3,6 %	IDN	45,5	KHM	54,4	FRA	9,8 %
KHM	2230,7	NPL	2414,1	ZWE	3,3 %	LAO	44,9	ETH	53,9	JPN	9,5 %
LAO	2229,8	IND	2412,8	HKG	3,3 %	KHM	44,8	IND	53,8	PRK	8,3 %
NPL	2223,1	MDG	2402,7	DJI	3,2 %	NPL	44,3	MDG	53,1	MDG	8,1 %
BGD	2219,6	VNM	2384,4	PRK	3,2 %	VNM	44,1	VNM	52,8	DJI	7,4 %
TLS	2202,0	BGD	2384,1	SGP	2,9 %	BGD	43,8	BGD	52,3	BHR	7,1 %
VNM	2199,1	TLS	2322,7	JPN	0,9 %	TLS	43,1	TLS	50,1	ZWE	6,1 %

ARE: United Arab Emirates AUS: Australia BDI: Burundi BGD: Bangladesh CPV: Cape Verde CZE: Czech Republic DJI: Djibouti ERI: Eritrea EST: Estonia ETH: Ethiopia FRA: France FSM: Federated States of Micronesia GAB: Gabon GNQ: Ghana GRD: Grenada HKG: Hong Kong IDN: Indonesia IND: India ISL: Iceland IRL: Ireland JAM: Jamaica JOR: Jordan JPN: Japan KGZ: Kyrgyzstan KHM: Cambodia KWT: Kuwait LAO: Lao People's Democratic Republic LCA: Saint Lucia LTU: Lithuania MDG: Madagascar MKD: The Former Yugoslav Republic of Macedonia MMR: Myanmar NPL: Nepal NZL: New Zealand OMN: Oman PRK: Democratic People's Republic of Korea PSE: State of Palestine PYF: French Polynesia QAT: Qatar SGP: Singapore SOM: Somalia TLS: Timor-Leste TON: Tonga USA: United States of America VCT: Saint Vincent and the Grenadines VNM: Viet Nam WSM: Samoa ZWE: Zimbabwe

The dissimilitude between weight and food energy can be explained, among others, by the differentiated height and age trends (Figure 2e and 2g). For instance, the French have a smaller energy demand than the Brazilians (Figure 2a), despite being heavier and taller (Figure 2c and 2e), which may be explained by an older population (Figure 2g). Likewise, Japanese and Indians now have similar food energy needs after marked differences in 1975 (Figure 2a). Food requirements remained almost constant in Japan, despite weight and height gains (Figure 2c and 2e), which may be explained by the fact that its population became the oldest (Figure 2g and 2h). On the contrary, the Indians' energy needs increased due to medium weight gains (Figure 2d) and moderate ageing (Figure 2e and 2f). The discrepancy between weight and food energy is also explained by other environmental, lifestyle and genetic factors[34,35].

Adults in all countries, except Madagascar and Rwanda, increased in average height (up to 4.5%) (Figure 2f), with a global range from -0.5 to 7.1 cm. However, some countries started to experience a decline in the average height after 1990 (Figure S3c). By 2014, 65 countries had declining average adult height, in spite of the generalized increases in the mean height of individuals born during the past century[11]. Worldwide, height gains at the societal level are slowing down, reinforced by the ageing of population. Generally, older adults, whose proportion in the population has been increasing, are shorter than their younger counterpart.

The changes in average age exhibited the largest variability (-8.8 to 25.8%) (Figure 2h), which translated to net reductions and increments of -3.6 to 10.7 years. Yet, ageing tends to accelerate in most countries[36] (Figure 2f and 2h and Figure S3).

Similar to the global results, our estimates on energy requirements across nations (2320-3210 kcal/cap/day) are higher than Hiç et al.[23] (1800-2800 kcal/cap/day) and comparable to Walpole et al.[22] (2318-3017 kcal/cap/day). Nonetheless, our ranking of the heaviest and lightest adults (Table 1), and thus food energy needs, slightly differs from the one made by Walpole and colleagues. For instance, in the upper range, we estimate the average United States' and United Arab Emirates' adult to weigh 81.3 kg and 77.8 kg respectively in 2005 (Dataset S1). Walpole and colleagues report 82 kg and 75.8 kg for the same countries. Similarly, in the lower range, we calculate 54.6 kg and 51.9 kg for Eritrea and Cambodia, while Walpole et al. report 52.1 kg and 55.9 respectively.

In terms of food energy requirements, we estimate an average of 2920 kcal/cap/day for the United States, while Walpole et al. reports 2874 kcal/cap/day. This difference of 46 kcal/cap/day, although relatively small (c.a. 1.5%), translates in 10 Gkcal per day given the country's adult population. A number equivalent to the food energy requirements of a country like Croatia or New Zealand which have approximately 3.4 million adults.

We attribute the differences between our numbers and Walpole et al. to the dissimilar sources of information and data treatment. In our case, to derive weight, height data was available for all cohorts and sexes in all countries but we use country average BMI values by sex. On the other hand, Walpole and colleagues counted with BMI numbers by age and sex but some information on height was missing and therefore completed by linear regression methods using data on countries of the same region. Both methods can yield under and overestimations in the weight of different population segments as well as in the country average. Thus, we highlight not only the need but the importance of having both historic age and sex disaggregated BMI information as well as sex and cohort height statistics to be able to produce better estimates on food requirements.

Closing Remarks. The interrelated dynamics between population, weight, height and age have implications for the food supply and demand as well as food security of the coming decades. We show that, in the 1975-2014 period, the rise in food demand was mainly driven by population numbers (116%), yet it was also affected in a non-negligible manner (13%) by changes in human biophysical traits (Figure 3). Thus, what previous analyses could have estimated as food surplus or waste might actually be mass sequestered in the bodies of the human lot.

Integrated metabolic and socio-demographic models can contribute to a better assessment of hunger worldwide[37], to distinguish losses and waste along the food value chain and to forecast food needs of evolving populations[23]. Furthermore, the increasing human mass, size and ageing phenomena have implications for resource use beyond food. Other energy and material connotations are foreseen for buildings, mobility, water, waste, sewage, furniture, clothing, and health care. Bigger humans tend to require larger living and sitting spaces and produce more waste[18], while an ageing population requires different economic goods[16].

Our study supports the importance of considering stock dynamics and the differentiation of cohorts and types (see Materials and Methods) across time for better understanding the changing needs of a population as well as the resource and infrastructures to satisfy these needs.

ASSOCIATED CONTENT

Supporting Information

The following files are available free of charge

Figures with additional results. (PDF)

Dataset with tables adult population, and average food energy requirements, weight, height and age at the global and national levels. (XLSX)

AUTHOR INFORMATION

Corresponding Author

[*] Phone: +57 3233753234. E-mail: luis.v.correa@ntnu.no

Author Contributions

F.V. conceived the study, gathered and processed the input data, developed the computer script, analyzed results and drafted the manuscript. G.V. analyzed results and drafted the manuscript. F.V. and G.V. contributed equally to the literature review, analysis of results, generation of figures and tables, and writing of the manuscript. D.M. contributed to the design and supervision of the study, and edited the manuscript.

Notes

The authors declare no conflict of interests.

ACKNOWLEDGMENTS

We thank Dr. Valentina Prado for insights, discussions, and critical reading of the manuscript.

REFERENCES

(1) Meadows, D. H.; Goldsmith, E.; Meadow, P. *The limits to growth*; Universe books New York, 1972; Vol. 381.

(2) Malthus, T. R. *An Essay on the Principle of Population As It Affects the Future Improvement of Society, with Remarks on the Speculations of Mr. Goodwin, M. Condorcet and Other Writers*, 1st ed.; London, J. Johnson: London, 1798.

(3) Lewis, S. L.; Maslin, M. A. Defining the Anthropocene. *Nature* **2015**, *519* (7542), 171–

180.

(4) Foley, J. Living by the lessons of the planet. *Science (80-.).* **2017**, *356* (6335).

(5) Fischer-Kowalski, M.; Krausmann, F.; Pallua, I. A sociometabolic reading of the Anthropocene: Modes of subsistence, population size and human impact on Earth. *Anthr. Rev. [online]* **2014**, *20* (10), 1–26.

(6) Fischer-Kowalski, M.; Swilling, M.; von Weizsäcker, E. U.; Ren, Y.; Moriguchi, Y.; Crane, W.; Krausmann, F.; Eisenmenger, N.; Giljum, S.; Hennicke, P.; et al. *UNEP (2011) Decoupling natural resource use and environmental impacts from economic growth, A Report of the Working Group on Decoupling to the International Resource Panel*; United Nations Environment Programme, 2011.

(7) Chertow, M. R. The IPAT Equation and Its Variants. *J. Ind. Ecol.* **2000**, *4* (4), 13–29.

(8) Dietz, T.; Rosa, E. A. Effects of population and affluence on CO2 emissions. *Proc. Natl. cademy Sci. United States Am.* **1997**, *94* (January), 175–179.

(9) Blanco, G.; Gerlagh, R.; Suh, S.; Barrett, J.; de Coninck, H. C.; Diaz Morejon, C. F.; Mathur, R.; Nakicenovic, N.; Ofosu Ahenkora, A.; Pan, J.; et al. Drivers, Trends and Mitigation. *Clim. Chang. 2014 Mitig. Clim. Chang. Contrib. Work. Gr. III to Fifth Assess. Rep. Intergov. Panel Clim. Chang.* **2014**, 351–412.

(10) Crist, E.; Mora, C.; Engelman, R. The interaction of human population, food production, and biodiversity protection. *Science (80-.).* **2017**, *356* (6335), 260–264.

(11) NCD Risk Factor Collaboration (NCD-RisC). A century of trends in adult human height. *Elife* **2016**, *5*, 1–29.

(12) Finucane, M. M.; Stevens, G. A.; Cowan, M. J.; Danaei, G.; Lin, J. K.; Paciorek, C. J.; Singh, G. M.; Gutierrez, H. R.; Lu, Y.; Bahalim, A. N.; et al. National, regional, and

global trends in body-mass index since 1980: systematic analysis of health examination surveys and epidemiological studies with 960 country-years and 9·1 million participants. *Lancet* **2011**, *377* (9765), 557–567.

(13) NCD Risk Factor Collaboration. Trends in adult body-mass index in 200 countries from 1975 to 2014: a pooled analysis of 1698 population-based measurement studies with 19·2 million participants. *Lancet* **2016**, *387* (10026), 1377–1396.

(14) Vaupel, J. W. Biodemography of human ageing. *Nature* **2010**, *464* (7288), 536–542.

(15) Lutz, W.; Butz, W. P.; Samir, K. C. *World population and human capital in the twenty-first century*; Oxford University Press, 2014.

(16) Lee, R. D.; Mason, A. *Population aging and the generational economy: A global perspective*; Edward Elgar Publishing: Cheltenham, 2011.

(17) FAO. *Human energy requirements: Report of a Joint FAO/WHO/UNU Expert Consultation*; Rome, 2001; Vol. 1.

(18) Heymsfield, S. B.; Bourgeois, B.; Thomas, D. M. Assessment of human energy exchange: historical overview. *Eur. J. Clin. Nutr.* **2016**, No. September, 1–7.

(19) Müller, M. J.; Geisler, C. From the past to future: from energy expenditure to energy intake to energy expenditure. *Eur. J. Clin. Nutr.* **2016**, No. September, 1–7.

(20) Westerterp, K. R. Control of energy expenditure in humans. *Eur. J. Clin. Nutr.* **2016**, No. September, 1–5.

(21) Hall, K. D.; Guo, J.; Dore, M.; Chow, C. C. The progressive increase of food waste in America and its environmental impact. *PLoS One* **2009**, *4* (11), 9–14.

(22) Walpole, S. C.; Prieto-Merino, D.; Edwards, P.; Cleland, J.; Stevens, G.; Roberts, I. The weight of nations: an estimation of adult human biomass. *BMC Public Health* **2012**, *12*

(1), 439.

(23) Hiç, C.; Pradhan, P.; Rybski, D.; Kropp, J. P. Food Surplus and Its Climate Burdens. *Environ. Sci. Technol.* **2016**, *50* (8), 4269–4277.

(24) Alexandratos, N.; Bruinsma, J. World agriculture: towards 2015/2030: an FAO perspective. *Land use policy* **2003**, *20* (4), 375.

(25) Rayfuse, R.; Weisfelt, N. *The Challenge of Food Security*; Edward Elgar Publishing, 2012; Vol. 327.

(26) West, P. C.; Gerber, J. S.; Engstrom, P. M.; Mueller, N. D.; Brauman, K. a; Carlson, K. M.; Cassidy, E. S.; Johnston, M.; MacDonald, G. K.; Ray, D. K.; et al. Leverage points for improving global food security and the environment. *Science (80-.).* **2014**, *345* (6194), 325–328.

(27) Porter, J. R.; Xie, L.; Challinor, A. J.; Cochrane, K.; Howden, S. M.; Iqbal, M. M.; Lobell, D. B.; Travasso, M. I. *Food security and food production systems*; 2014.

(28) Valin, H.; Sands, R. D.; van der Mensbrugghe, D.; Nelson, G. C.; Ahammad, H.; Blanc, E.; Bodirsky, B.; Fujimori, S.; Hasegawa, T.; Havlik, P.; et al. The future of food demand: understanding differences in global economic models. *Agric. Econ.* **2014**, *45* (1), 51–67.

(29) Shafiee-Jood, M.; Cai, X. Reducing Food Loss and Waste to Enhance Food Security and Environmental Sustainability. *Environ. Sci. Technol.* **2016**, *50* (16), 8432–8443.

(30) Xue, L.; Liu, G.; Parfitt, J.; Liu, X.; Van Herpen, E.; Stenmarck, A.; O'Connor, C.; Östergren, K.; Cheng, S. Missing food, missing data? A critical review of global food losses and food waste data. *Environ. Sci. Technol.* **2017**, acs.est.7b00401.

(31) Vásquez, F.; Løvik, A. N.; Sandberg, N. H.; Müller, D. B. Dynamic type-cohort-time approach for the analysis of energy reductions strategies in the building stock. *Energy*

Build. **2016**, *111*, 37–55.

(32) Müller, D. B. Stock dynamics for forecasting material flows—Case study for housing in The Netherlands. *Ecol. Econ.* **2006**, *59* (1), 142–156.

(33) United Nations; Department of Economic and Social Affairs; Population Division. World Population Prospects: The 2015 Revision, DVD Edition http://esa.un.org/unpd/wpp/Download/Standard/Population/ (accessed Apr 7, 2016).

(34) Deaton, A. Height, health, and development. *Proc. Natl. Acad. Sci.* **2007**, *104* (33), 13232–13237.

(35) Dubois, L.; Ohm Kyvik, K.; Girard, M.; Tatone-Tokuda, F.; Pérusse, D.; Hjelmborg, J.; Skytthe, A.; Rasmussen, F.; Wright, M. J.; Lichtenstein, P.; et al. Genetic and environmental contributions to weight, height, and bmi from birth to 19 years of age: An international study of over 12,000 twin pairs. *PLoS One* **2012**, *7* (2).

(36) Lutz, W.; Sanderson, W. C.; Scherbov, S. The coming acceleration of global population ageing. *Nature* **2008**, *451* (7179), 716–719.

(37) FAO; IFAD; WFP. *The State of Food Insecurity in the World: Meeting the 2015 international hunger targets: taking stock of uneven progress.*; 2015.

TOC ART