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Stefan Pauliuk,

Karin Sjöstrand,

and Daniel B. Müller

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Transforming the Dwelling Stock to reach the 2°C Climate Target – Combining MFA and LCA Approaches for a Case Study on Norway

Stefan Pauliuk,[*,1] *Karin Sjöstrand,*[1] *and Daniel B. Müller*[1]

1) Industrial Ecology Programme and Department of Hydraulic and Environmental Engineering,
Norwegian University of Science and Technology, Trondheim, Norway

* Address correspondence to: stefan.pauliuk@ntnu.no; telephone: +47-735-95156;

ABSTRACT:

Residential buildings account for about one third of the final energy demand in Norway. Many cost-effective measures for reducing heat losses in buildings are known and their gradual implementation may make the building sector one of the largest contributors to climate change mitigation.

To estimate the sectoral reduction potential we model a complete transformation of the dwelling stock by 2050 by both renovation and re-construction with different energy standards. We propose a new dynamic stock model with an optimization routine to identify and prioritize buildings with the highest energy saving potential. The sectoral boundary is extended by including the energy and carbon footprint of the construction industry.

Despite an expected population growth of almost 50% between 2000 and 2050, sectoral carbon emissions may drop between 30 and 40% compared to emissions in 2000 for scenarios where the stock is completely transformed by either re-construction or ambitious renovation. Due to the lower upstream impact, renovation to passive house standard allows sectoral emissions to decline faster and is therefore preferable from the viewpoint of carbon emissions.

Transformation however, is not sufficient to achieve emission reduction of 50% or more as required on average to limit global warming to 2°C, because hot water generation, appliances, and lighting will dominate the sectoral footprint once the stock has been transformed. A first estimate on the impact of energy efficiency and lifestyle changes in the non-heating part of the sector reveals a maximal reduction potential of ca. 75%.

KEYWORDS: GHG emission abatement; sectoral targets; residential buildings; energy efficiency; MFA; LCA; renovation;

Introduction

Buildings as hope for climate change mitigation: Households account for about 25% of global final energy consumption. Two thirds are related to heating and hot water generation while appliances including cooking and lighting make up the rest (IEA 2008a). Urbanization and economic growth mainly in developing countries are expected to drastically increase the dwelling stock; and given similar trends in other sectors the IEA report states that “A global revolution is needed in ways that energy is supplied and used.” (IEA 2008a) This statement is motivated mainly by the substantial reduction of global greenhouse gas emissions of 50-85 % by 2050 that is required to limit global warming to 2°C as proposed in table 3.10 of chapter III-3 of the Forth IPCC Assessment Report (IPCC 2007).

To achieve this revolution energy efficiency is considered central (IEA 2008b) with a suggested contribution of more than 50% to overall savings. A large number of studies reviewed in chapter III-6 of (IPCC 2007) identified the building sector as potential main contributor to energy efficiency. A wide portfolio of appropriate building techniques and other efficiency measures is known, available on the market in most developed countries, and in many cases cost-efficient (IPCC 2007; McKinsey 2009).

Concurrently, chapter III-6 reports that emissions from the building sector are expected to rise from 9 Gt in 2004 to 11-16 Gt in 2030, mainly depending on future economic growth in the developing world. Given climate change as global constraint to future use of fossil fuels, it is the responsibility of the developed nations to take the transformation of the building stock serious in order to facilitate economic development elsewhere in the world. Recent policy proposals (Kelly 2009; European Commision 2011) make similar arguments and suggest sectoral reduction targets of 80% and beyond.

Objective and literature review: We provide estimates on the future energy demand and carbon footprint of the entire dwelling stock. Following the notion of a revolution demanded by the IEA report we model a complete transformation of the building stock by 2050 through successive application of different energy efficiency measures to all dwellings.

We use residential buildings in Norway as a case study since this stock is quite well investigated, passive houses and renovation are being promoted already, and the economic situation of country and people allows to apply these measures on a large scale. Country-specific obstacles are the high latitude which leads to relatively low solar irradiance and a rather cold climate. Hydropower dominates the electricity mix and is widely used for heating purposes (Statistics Norway 2011a) which impedes more useful application of this valuable energy carrier.

A recent study on the historic development of energy consumption in the Norwegian dwelling stock (Sandberg et al. 2011) showed that energy consumption has doubled between 1960 and 2005 to a rather constant level of ca. 45 TWh/yr. The increase is a result of steadily increasing population and useful floor area (UFA) per dwelling and a decreasing number of persons per dwelling (Bergsdal et al. 2007); while the recent flattening can be explained by increasing renovation activity and implementation of new building codes, TEK-07 and TEK-10 (Bolig- og Bygningsavdelingen 2011), that enforce more energy efficient buildings. During the same period, the sectoral carbon footprint has decreased by ca. 40% mainly due to a sharp decline in the use of heating oil and because the Norwegian electricity mix which contains mostly hydropower was assumed by (Sandberg et al. 2011).

Several studies estimated the mid and long term potential of energy efficiency measures in Norway: (Sartori et al. 2009) analyzed the impact of shifting from direct electric heating to heat pumps and wood stoves combined with renovation and found that by 2035, up to 17 TWh/yr or ca. 2500 kWh/person*yr of electricity can be saved compared to 2005. Their scenarios are based on extrapolating present rates of demolition, renovation, and new construction rather than trying to derive them from external targets. The model treats the existing building stock as homogenous and the study does not cover upstream impacts and carbon emissions from material production, construction, and energy supply.

A similar approach has been employed by (Reinås 2009), and the total savings of final energy use in 2040 is estimated to be 23 TWh/yr compared to 2007.

Finally, (Sandberg and Brattebø 2012) use a scope and system boundary similar to this study but do not consider scenarios that exhaust the full potential of energy efficient buildings. Hence they find energy consumption will continue to rise until 2030 mainly due to the growing stock and increasing energy demand upstream, whereupon it will start to decline slightly. This article also contains an excellent literature review.

Scope

The previous studies do not cover the following topics and questions:

(1) Various sources on energy consumption in buildings exist: Historic energy statistics, building archetypes, building codes, and proposals for renovation measures. How can the heating energy demand of existing buildings, renovated buildings, and new buildings be determined in a comparable way?

(2) What is the energy and carbon footprint of present renovation measures in comparison to demolition and subsequent reconstruction?

(3) Given the results from (1) and (2), is a complete transformation by either demolition and reconstruction or renovation of the dwelling stock sufficient to reduce the sectoral carbon footprint by 50% or more by 2050? What additional reductions could be achieved by different lifestyle and savings from hot water generation and appliances?

This study addresses these questions as follows:

(1) We publish a common **physical model of heating energy demand** and apply it to a set of archetypes for existing buildings, to new buildings erected according to the present standard, and to the renovation measures we propose.

(2) Comparative LCA: A life cycle inventory of a new standard and passive house has recently been compiled by (Dahlstrøm 2011). We define two renovation packages, compile the inventory of renovation materials and complete it with parts of the inventory for new buildings that is common for both reconstruction and renovation. The energy directly consumed by households is covered as well.

(3) Dynamic MFA: A dynamic stock model of the entire dwelling stock with externally given rates for demolition and renovation allows to *model complete transformation* of the stock by 2050. Such a transformation has been described earlier for different regions in Switzerland by (Kytzia and Dürrenberger 1999) and (Müller et al. 2004).

We track individual cohorts, types, and renovation levels and apply an *optimization routine* in order to target the buildings with the highest saving potential. We scale up the LCA results from part (2) to obtain a more complete energy and carbon footprint of the dwelling stock (Kohler and Hassler 2002). A scenario analysis explores the effect of different energy efficiency strategies.

Benefits

The model estimates the maximal energy saving potential by 2050 within the given sectoral boundaries, lifestyle parameters, efficiency measures, and turnover rates. In the supplementary material we describe the complete chain of calculations and assumptions from the building archetypes applied to specific and total energy consumption and further to the sectoral carbon footprint. We demonstrate how MFA studies can be extended systematically by including standardized LCAs and how life cycle inventories of individual products can be scaled up to the sector or national level by connection them to a dynamic stock model.

Methodology

The complete methodology, data handling, and inventories are described in the supplementary information. The system (Fig. 1) comprises three modules (a) – (c):

(a) MFA model

A dynamic stock model of the heated floor area (HFA) of all residential buildings in Norway including the heating systems is balanced for both energy and HFA (Fig. 1, center). Energy for domestic hot water (DHW) and appliances is included as it accounts for a large part of total household energy consumption and can significantly influence the thermal balance of a house. The heated part of the dwelling stock *HFA* is tracked over time *t* and is split onto different cohorts *c*, building types *T*, energy standards *r*, and heating systems *s* to model different levels of energy consumption, building geometries, and energy sources. Each heating system *s* uses a specific fuel type *q*. A brief description of the indices follows:

The model **time *t*:** runs from 2010 to 2060 in steps of one year. 2050 is the target year used for interpretation.

According to the detailedness of energy consumption data available, we distinguish five historic **cohorts *c*** (<1950, 1951…1970, 1971…1980, 1981…1995, 1995…2010), and 50 future cohorts (2011-2060)

Three **building types *T*** are distinguished according to their different dimensions and energy consumption: single family houses, detached houses, and apartment blocks.

Six different **energy standards *r*** are considered: The existing stock is split into not renovated and previously renovated buildings according to the estimates given in (Thyholt et al. 2009). For future major renovation we consider to classes, cf. below. For new buildings we consider both the current building code (TEK-10) as well as passive houses which are standardized in (Standard Norge 2007) and (Standard Norge 2010), respectively.

We distinguish seven **heating systems *s*** according to (Statistics Norway 2011a): Direct electric, heat pumps, wood stoves, district heating, and oil heating. Future heat pumps and wood stoves are treated as separate systems as they are expected to become more energy-efficient.

We consider four **energy carriers *q*:** electricity, district heating, wood, and domestic fuel oil. Each heating system s is assigned a fuel type q and the matrix $\eta(s,q)$ indicates the energy demand of type q per unit of heat supplied to the dwelling by system s.

Stock dynamics

As in previous studies (Hu et al. 2010; Bergsdal et al. 2007), our model is stock-driven which means that the total demand for HFA is determined externally by population $P(t)$ and the lifestyle parameters persons per dwelling $PpD(t)$ and heated floor area per dwelling $HFApD(t)$. (Equ. 1)

$$HFA(t) = \sum_{\mathrm{t',T,r,s}} HFA(t,t',T,r,s) = \frac{P(t)}{PpD(t)} \cdot HFApD(t) \qquad (1)$$

The *turnover* of the stock and hence the opportunity to reduce energy consumption is given by the annual renovation and demolition flow. Two types of dynamic MFA models that model the turnover of a stock have evolved: The leaching model (van der Voet et al. 2002; Baccini and Bader 1996) assumes that the annual outflow O is proportional to the total stock S: $O(t) = r \cdot S(t)$. The stock is considered homogenous, no cohorts or other dwelling features such as different energy characteristics are distinguished. The lifetime model (Müller 2006; Baccini and Bader 1996) keeps track of individual cohorts and has recently been extended to distinguish different product types within a given cohort (Pauliuk et al. 2012). Neither model however is capable of determining an optimal solution described in point (3) of the introduction: A leaching model allows for complete transformation of the stock by appropriate choice of the leaching rate r but not for optimization as the homogenous stock does not allow us to identify the buildings that have highest saving potential. A lifetime model is too rigid as the pre-determined lifetime distribution locks certain cohorts from being demolished, and hence the model solution is in general not minimal. Observed lifetimes of residential buildings vary a lot across the world (from Japan with below 50 years (Komatsu et al. 1994) to the western world with 100 years and more) (Bradley and Kohler 2007; Müller et al. 2007) and it is not clear to which extent lifetime estimates for historic cohorts are suitable to model the transformation of the dwelling stock in light of climate change. The same criticism applies to (Sartori et al. 2008) where the authors use a pre-determined function to model the renovation activity within a certain cohort. We propose the following procedure as a synthesis of the two model types:

0) PREPARE: An initial break-down of the existing dwelling stock *HFA(2010,t',T,r,s)* is estimated from statistics and the literature. The subsequent calculations are performed successively for all years *t*, starting in 2011.
1) TARGETS: The HFA stock from the last year *t-1* is transferred into the current year *t*, and the *targets* for renovation and demolition, $\hat{D}(t)$ and $\hat{R}(t)$, are determined from the externally given rates *d(t)* and *r(t)*:

$$\hat{D}(t) = d(t) \cdot HFA(t); \quad \hat{R}(t) = r(t) \cdot HFA(t) \tag{2}$$

2) OPTIMIZATION: To break down the targets $\hat{D}(t)$ and $\hat{R}(t)$ onto specific cohorts, types, and energy standards in year *t* we apply two linear programs, one for demolition and replacement and one for renovation, with the objective of maximizing the annual heating energy saved compared to new and renovated buildings, respectively. Upstream demand is not included here since typical amortization periods of energy efficiency measures are longer than one year.
3) STOCK BALANCE: Renovated buildings re-enter the stock and the parameter α determines the split between renovation package I and II, (cf. below). Demand for new construction is determined from area balance of the HFA stock; it is split onto different indices by applying the share of different types, standard and passive houses, and heating systems.

Once the stock is completely transformed by either demolition or renovation, the targets cannot be reached anymore. *d(t)* and *r(t)* are set in a way that this will be the case just before 2050.

(b) Energy demand: The specific energy consumption per square meter and year for heating $e_H(c,T,r)$, domestic hot water production $e_{DHW}(c,T,r)$, and appliances $e_A(c,T,r)$ determine the total direct energy demand of all households by multiplication with the detailed stock *HFA(t,c,T,r,s)* (Equ. 3):

$$E_{MARKET}(t,q) = \sum_{\mathrm{c,T,r,s}} HFA(t,c,T,r,s) \cdot \left(\frac{e_H(c,T,r) + e_{DHW}(c,T,r)}{\eta(s,q)} + e_A(c,T,r) \cdot \delta_{1q} \right) \qquad (3)$$

The Kronecker-delta δ_{1q} indicates that appliances demand electricity only $(q=1)$.

Derivation of specific energy consumption

The building archetypes for Norway given in (Myhre 1995; Thyholt et al. 2009) include the dimensions and heat transfer coefficients (U-values) for the different building components which enable us to calculate the monthly heat losses based on long-term records on average outside temperatures. Adding solar gains and internal gains from appliances, lighting, and people according to the present standard (Standard Norge 2007) allows us to determine the average monthly heating demand for each archetype. The current building code requires a building design without active cooling (Bolig- og Bygningsavdelingen 2011) and hence we only include the net heat demand for the cold months in the annual balance (Table 1).

A recent expert report (Arnstad 2010) submitted to the Norwegian Ministry of Local Government and Regional Development proposes that in the future, all major building retrofits shall be carried out according to low-energy and passive standard from 2015 and 2020 on, respectively. We hence model two renovation levels: package I (renovation to energy level of current building code TEK-10) and II (renovation to passive house standard). Both packages comprise higher insulation, air tightness, and heat recovery of ventilation and decreased U-value of windows and thermal bridges. The net heat demand of renovated buildings is determined using the same method as above by applying the parameters given in Table 2. For new buildings heating energy demand is calculated accordingly by combining the dimensions of the latest cohort considered by (Myhre 1995) with the parameters according to TEK-10 and passive house standard, respectively (Table 2). We apply the resulting $e_H(t',T,r)$ to all future cohorts. This simplification can be justified considering that the resulting specific heating demand for passive buildings (Table 2) is small compared to the standard for energy consumption for DHW (30 kWh/m^2·yr) and appliances (40 kWh/m^2·yr) (Standard Norge 2007).

(c) LCA system

Goal and scope: We estimate the cumulative energy demand and the carbon footprint of the following functional units: 1 MJ of energy carrier *q*, 1 m² of new or renovated buildings of type T and energy level *r*, and 1 m² being demolished. (left and right subsystems in Fig. 1). These functional units are scaled up with the demand from the use phase (subsystem a) to yield the system-wide impact. We assume no technological change in the inventory system over time; the LCA system serves as constant background of the transformed dwelling stock.

Inventory analysis: For new construction of Norwegian single-family houses both according to current building code and passive standard we refer to a recent case study (Dahlstrøm 2011). It contains a detailed material and energy inventory according to subsystem c in Fig. 1 and serves as approximation for the impact of constructing semi-detached houses and blocks. To estimate the upstream impact of renovation activities we compiled the material inventory according to the building archetype dimensions and the renovation packages defined in Table 2 and determined their energy requirement and carbon footprint from EcoInvent v2.2. To be consistent with (Dahlstrøm 2011) we assume that for windows, doors, and the façade renovation has the same impact as new construction. Details are provided in the supplementary material.

Impact assessment:

Cumulative energy demand (CED) is determined according to the CED method applied in SimaPro (PRE - Product Ecology Consultants 2008), while the ReCiPe method, hierarchist midpoint version 1.03 (Goedkoop et al. 2009) is used to estimate the carbon footprint (CC). Allocation of co-benefits of by-products and waste streams is done according to EcoInvent v2.2.

There is no consensus on the carbon footprint of electricity consumed in Norway (Thyholt 2006). In 2009, 15 TWh of hydroelectricity were exported which is about 11% of the domestic production (Engvall and Løvås 2010), 6 TWh were imported to compensate peak loads. Coal power from Finland or Denmark has been identified as marginal electricity (Thyholt 2006). Moreover, Norway sells renewable electricity certificates to other European countries which further decreases the amount of hydropower *sold* on the domestic market (Norwegian Water Ressources and Energy Directorate 2009). We therefore apply not the Norwegian but the Nordic electricity mix. For the other fuels the carbon footprints are taken from a Norway-specific study (Thyholt and Hestnes 2008).

Data for scenario modeling

Population forecasts are taken from (Statistics Norway 2011b), and for persons and UFA per dwelling we refer to the scenarios in (Bergsdal et al. 2007). A recent study estimated the demolition rate in 2007 to be 0.6% (Reinås 2009), while for 2003, 0.4% of the dwelling stock underwent renovation carried out by professionals. While the latter figure does not include renovations done by house owners themselves we still believe that this figure is a suitable estimate since applying either Package I or II requires professional assistance. In 2010, the share of UFA in single-family houses, detached houses, and blocks in new construction was 51%, 12%, and 37%, respectively (Statistics Norway 2011c).

Scenario definition:

We conduct a sensitivity analysis and propose a set of scenarios (Table 3): The baseline (1) serves as reference as it contains medium estimates for population, persons per dwelling, and HFA per dwelling, and applies business-as-usual to renovation and demolition level and the share of different types and heating systems. Passive houses and package II are not considered as by today, only very few examples exist in Norway (Dokka et al. 2009; Tunmo 2011). Scenario 2 (optimization routine is replaced by uniform renovation) and 3 (the existing building stock is not changed at all) demonstrate the saving potential already included in the baseline. Scenarios (4)-(14) explore the potential of ambitious single parameter variations. Scenarios 9, 10, and 15-17 examine several pathways to completely transform the stock by 2050 by combining demolition, passive houses, and standard and passive rehab. Out of these, the transformation bottom (TB, 17) will be shown to have lowest sectoral emissions in 2050; it comprises a constantly high renovation rate of 2 %/yr with a 90% share of package II and all new houses being passive houses from 2020 on. Starting from TB we consider two branches: Scenarios (18)-(22) determine changes due to different population and lifestyle. Scenarios (23)-(25) contain a cascade of three measures: (23) maximal share of heat pumps, (24) reduced energy demand for DHW, and (25) reduced energy demand for appliances. Finally, the bottom line (26) combines the most advanced scenarios of both branches, (22) and (25), for the medium population estimate. We refer to the supplementary material for a detailed overview.

Results

Stock and energy consumption in 2010

Not renovated single family houses with a heating energy demand between 80 and 275 $\text{kWh/m}^2\cdot\text{yr}$ account for about 40% of the total stock (Table 1). This is up to four times more than the energy demand for domestic hot water and appliances (70 $\text{kWh/m}^2\cdot\text{yr}$) which serves as benchmark. The older and smaller the building the higher the heat losses: single family houses from before 1950 have about four times higher energy specific energy consumption than recently built blocks. Most of the oldest cohorts have already been renovated but compared to Package I and II (Table 2), the reduction potential remains large. Single family houses built before 1970 account for about one third of total direct energy consumption; renovating or replacing these houses will require several decades. Another third is used by single family houses younger than 40 years where the remaining energy saving potential is smaller. The last third is consumed in detached houses and blocks, where the pre-1970 cohorts are contributing with ca. 50%.

Specific energy consumption and upstream impacts

Applying the proposed renovation measures to the building archetypes can substantially reduce heating energy demand to 30-55 $kWh/m^2 \cdot yr$ for package I and 10…25 $kWh/m^2 \cdot yr$ for package II, respectively which is the same range as TEK-10 and passive buildings (Table 2). DHW and appliances (together 70 $kWh/m^2 \cdot yr$) will account for the largest part of energy consumption for all future new and renovated buildings.

While the difference in upstream energy and carbon footprint between TEK-10 and passive houses is below 20%, both are a factor 2-3 bigger than the corresponding figures for renovation (Fig 2). The building shell including the insulation material accounts for ca. 50% of the impact for new buildings, and the impact of renovation is dominated by mineral wool. The figures presented here underline the importance of upstream impacts: Given a lifetime between 50 and 100 years, new construction contributes with 15-40 $kWh/m^2 \cdot yr$ to life cycle average energy demand which is about the level of space heating demand in passive houses.

Single parameter variation and stock transformation

Despite an anticipated population growth from 4.9 to 6.6 million by 2050, baseline emissions will fall moderately to 92% of the benchmark (Table 3). This is a result of the gradual replacement of old buildings with TEK-10 houses and renovation to package I with the current turnover rates of around 0.5 % per year. Scenarios 2 and 3 demonstrate the impact of the optimization routine and the relatively low turnover rates of the baseline. Increasing the share of package II and the share of blocks (scenarios 4 and 8) leads only to slight changes in emissions. A level of 80…89% can be achieved by a change in lifestyle (6-7), the introduction of passive houses (11), new heating systems (12), and a lower demand for DHW and appliances (13-14). Transforming the whole stock by either demolition or renovation has the highest impact on baseline emissions, leading to 72% in 2050 (scenarios 9-10).

The maximal impact of the different transformation measures depends on a thorough combination of single parameter variations. Combining demolition with erection of passive houses can lower emissions to 65%, whereas renovation to package I yields 69% only (scenarios 15-16). If package II is applied widely however, a level of 62% can be achieved (scenario 17). This scenario is called ‘transformation bottom’ (TB) and is the starting point for subsequent analysis.

Beyond insulation

We consider two paths of further development: First, scenarios 18-22 consider moderate changes in lifestyle parameters similar to (Bergsdal et al. 2007). Increasing the number of persons per dwelling by 15% or a corresponding opposite change for HFA per dwelling will reduce emissions down to ca. 50 % in 2050 (18-19), and combining the two measures will exceed the 50% target (45% in 2050, scenario 22). The scenarios including high and low population estimates (20-21) are included for reasons of completeness and not used in the further analysis. Second, a cascade of measures comprising increased share of heat pumps, complemented by reduced demand for DHW and finally appliances leads to reductions to 49%, 45%, and 33%, respectively (scenarios 23-25). The bottom line combines scenarios 22 and 25 and results in a 77% reduction of the sectoral carbon footprint by 2050.

Heated Floor Area

For all scenarios except those including lifestyle changes the HFA stock will grow from 240 to ca. 325 million m^2 by 2050 (Fig. 3). The share of different renovation levels heavily depends on the scenario. In 2050, the baseline stock will consist of ca. 60% TEK-10 houses, 20% Package I renovated buildings, and 20% already existing buildings without further renovation. The situation changes drastically if the stock is transformed: For the passive-demolition scenario (15) 2/3 of the stock will be passive houses by 2050. For the transformation scenarios based on renovation, 1/3 of the stock will be passive houses and ca. 50% will be package I or II renovated houses by 2050.

Sectoral energy demand and electricity saved:

Compared to the sectoral energy demand of 45 TWh in 2000 of which ca. 90% is directly consumed by households, substantial reductions are possible (Table 4a): by transformation up to 35% (15-17), by lifestyle changes (18-22) and combined measures (23-25) up to 60 %, and for the bottom line up to 70%. By applying the most ambitious measures, 7 TWh/yr of electricity or ca. 20% of the 2000 level can be saved already in 2020 (Table 4b). This figure could increase to more than 20 TWh/yr or 60% saved from 2040 on. Even for less ambitious and single-measure scenarios electricity savings will be more than 30% and hence, the dwelling sector has a huge potential of contributing to energy security and of allowing hydroelectricity to be used in e.g., transportation.

Accumulated emissions

We present the accumulated energy use over the period 2011-2050 (Fig 4a) which allows our results to be interpreted according to the budget approach (WBGU 2009). The benefits of a large number of passive houses in the demolition scenario (15) are partly offset by a substantial increase in upstream impacts and hence, the transformation scenario based on package II (17) has higher accumulated savings than the demolition scenario. For all scenarios including transformation, electricity for appliances and lighting accounts for more than 50% of accumulated energy demand. Any debate on energy saving that goes beyond large scale application of passive houses or renovation should consider this. The three columns on the right (22/25/26) show the aggregated impact of lifestyle, savings in DHW and appliances, and their combination.

A similar picture holds for the accumulated CO_2 emissions (Fig. 4b), except that the demolition scenario (15) does not lead to a significant reduction compared to the baseline. The reason is that the energy used upstream is more carbon intensive than the energy consumed directly which is mostly electricity from the Nordic grid.

Discussion

How to transform the dwelling stock: Upstream and downstream impacts of new dwellings and renovation materials play a significant role in determining which combination of parameters has the highest reduction potential: A complete demolition of the stock with simultaneous enforcement of passive houses will yield substantial emission reductions by 2050; however, the accumulated emissions will hardly differ from the Baseline (Fig. 4). Ambitious renovation to passive standard leads to large emission reductions from the beginning on and from a carbon point of view, it is preferable both on the scale of a single house and of the entire stock. Present annual retirement rates of buildings in at least 10 European countries are below 0.5% (IEA 2008a) which emphasizes the difficulty of achieving the reduction goal by demolition.

One must not forget however, that after 2050, emissions must remain on a low level. Hence the transformation of the stock has to happen without the accumulation of a large maintenance or replacement backlog for the sake of reaching the 2050 target. In practice this means that renovation to passive house standard should only be applied in cases where the building core allows for a long functional life far beyond 2050, the necessary renovation measures are feasible from an engineering point of view, and the resulting building has acceptable functionality and esthetics. Case studies for passive rehabilitation in Scandinavia have focused on blocks so far (Dokka et al. 2009; SINTEF and NTNU 2011) and it remains to be shown to which extent and at which costs the proposed packages are applicable to single family houses which have the highest saving potential.

Reducing the sectoral carbon footprint by at least 50% as required to limit global warming to 2°C cannot be achieved by transforming the stock; additional measures such as lowering consumption from hot water generation or appliances and changes that impact the lifestyle such as smaller dwellings and more people per dwelling are required. Norway as one of the wealthiest countries should aim at a reduction beyond the minimal requirement, especially for the building sector which is expected to contribute over-proportionally and where several cost-effective measures exist (McKinsey 2009). If all measures proposed here would be applied to full extent by 2050, the sectoral carbon footprint could be reduced by more than 75% while the population grows further; and up to 25 TWh/yr of electricity could be saved and made available to other sectors such as transport or the oil industry, or be exported to continental Europe (Dokka et al. 2009).

Combining dynamic stock models with LCA studies Seen from an MFA perspective, we showed that including upstream and downstream impacts in a systematic way adds a new dimension to sectoral approaches that focus on the use phase alone. Especially for passive houses upstream emissions cannot be neglected due to the low energy consumption during use.

Our MFA model provides the opportunity to scale up an LCA of a single house to the national level in a meaningful way: A single passive house can lead to life-cycle energy savings of far more than 50% but the inertness and persistence of the building stock may delay full-scale penetration by several decades. Our dynamic stock model allows to estimate the impact of new building technologies over time and their eventual contribution to energy security and climate change mitigation.

Several sub-systems were added to the MFA study when life cycle inventories from different sources were forged into one model. Transparent and congruent system boundaries are essential to allow for comparison of the impacts of different measures and technologies. Double counting may occur if parts of the MFA system are covered by the inventories as well: e.g., a similar analysis of the transport sector would overestimate the sectoral footprint if freight transport was also covered by the inventories for material and energy. Energy demand in the dwelling sector is categorized as final consumption and is not part of any upstream inventory. Further spread of home offices may however blur sectoral boundaries in the future.

Effects beyond the sectoral boundary, limitations of the model: While a change from single-family houses to detached houses or blocks showed negligible impact on total energy consumption there may be other benefits from moving to more dense settlements due to increasing possibilities for public transport and generally smaller distances to shopping centers and work places, especially as population is expected to rise further. No temporal changes in the upstream and downstream system, which is mostly based on the 2007 version of EcoInvent, were assumed. This is a clear limitation as industries are likewise requested to reduce their carbon footprint either by increasing energy and material efficiency or the development of new construction materials and technologies such as carbon capture and storage. These changes could lead to a substantial reduction of the upstream impacts. Still we believe that present upstream impacts are a reasonable approximation and suitable to inform decisions on which pathway to take: To implement the list of measures examined here in the entire stock will take several decades. Hence action should start as soon as possible, and the earlier transformation happens the higher the accumulated benefits and the more accurate the assessments made based on the present inventory. The way recycling is modeled can significantly change the upstream impact figures. In 2006, only ca. 27% of construction waste in Norway was re- or down-cycled, and the present inventory neglects recycling and assumes instead that all combustible waste is incinerated which is in line with the current policy target in Norway (Dahlstrøm 2011). This limitation must be overcome when applying the model to sectors where recycling is crucial, e.g., when studying metals in transportation.

Rebounds and barriers:

As heat losses of buildings are minimized during transformation, energy for hot water and appliances becomes the dominant contributor to sectoral energy demand. Savings within these activities may require behavioral change or lower levels of consumptions while at the same time, rebound effects may occur both within and beyond the sector boundary (Barker et al. 2009). It becomes clear that energy efficiency alone, especially if it only affects energy for space heating, may not be sufficient to achieve the substantial sectoral reductions required to combat climate change. While rebound effects within a developed country may impede climate change mitigation, rebounds on a global scale are partially desirable because they mean nothing else than that developed countries set free resources to allow growth in developing countries under a global constraint on carbon emissions.

When deciding which measures to implement to which extent costs will be important, but market failures and other barriers will have to be overcome as well (McKinsey 2009; IEA 2008a). Public institutions will have to play a major role in enforcing wide-scale application of energy saving either by legislation, by setting suitable default options, or by providing financial incentives to make sure that the decisions made on the micro level are in line with the climate target.

We showed that residential buildings in Norway can play a major role in reducing the country's energy demand and carbon footprint. While the numeric results are country-specific, the proposed procedure of complete stock transformation and the combination of dynamic stock model and upstream inventory can be applied to any sector in any developed country. Early implementation of available, cost-efficient measures may quickly yield net savings, enable us to speed up the learning process, and determine whether the mitigation efforts will eventually lead to success.

About the authors

Stefan Pauliuk is a PhD student and Daniel B. Müller a professor affiliated with the Industrial Ecology Programme and the Department of Hydraulic and Environmental Engineering at the Norwegian University of Science and Technology (NTNU), Trondheim, Norway. Karin Sjöstrand wrote her master thesis on in the group of Prof. Müller (Sjöstrand 2011) and works now with CO2FOCUS NORDIC.

Supporting Information Available

Additional Supporting information may be found in the online version of this article:

Supplement S1: The complete system definition and model approach, data sources, data treatment, and additional results.

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TABLES

Table 1: Heated floor area (HFA), heating energy demand per m^2, and total energy demand including warm water and appliances for 2010.

2010	**HFA (million m^2)**			**Heating energy demand ($kWh/m^2 \cdot yr$)**			**Total energy demand (TWh/yr)**		
	Single	**Detached**	**Blocks**	**Single**	**Detached**	**Blocks**	**Single**	**Detached**	**Blocks**
Cohort	**Not renovated**			**Not renovated**			**Not renovated**		
< 1950	5	1	2	275	250	231	1.7	0.5	0.6
1950-1970	27	9	7	141	152	118	5.7	2.0	1.3
1971-1980	27	7	6	139	98	91	5.7	1.2	1.0
1981-1990	26	7	3	93	72	72	4.3	1.0	0.4
1991...2010	15	7	5	80	95	64	2.2	1.2	0.6
	Previously renovated			**Previously renovated**			**Previously renovated**		
< 1950	27	6	6	139	125	124	5.7	1.1	1.1
1950-1970	12	4	2	96	86	83	1.9	0.6	0.4
1971-1980	0	0	0	132	90	83	0.0	0.0	0.0
1981-1990	0	0	0	93	72	72	0.0	0.0	0.0
1991...2010	15	7	5	62	76	45	1.9	1.0	0.5
Sum	**154**	**49**	**36**				**29**	**9**	**6**
Total	**Total HFA (million m^2)**		**238**				**Total demand (TWh)**		**44**

Table 2: Renovation of existing buildings and new construction: overview of parameters that determine heat losses to the environment and the resulting figures for heating energy demand

Physical properties of building components					
Parameter	**Package I**	**Package II**	**TEK-10, small**	**TEK-10, detached and blocks**	**Passive houses**
Wall	add 200 mm mineral wool	add 350 mm mineral wool	0.18 W/m^2K	0.18 W/m^2K	0.15 W/m^2K
Ceiling	add 200 mm mineral wool	add 350 mm mineral wool	0.13 W/m^2K	0.13 W/m^2K	0.13 W/m^2K
Floor	add 100 mm mineral wool	add 200 mm mineral wool	0.15 W/m^2K	0.15 W/m^2K	0.15 W/m^2K
U-values windows (W/m^2K)	1.2	0.8	1.2	1.2	0.8
Thermal bridges (W/m^2K)	0.07	0.05	0.03	0.06	0.03
Air tightness (h^{-1}@50Pa)	2.5	1	2.5	1.5	0.6
Ventilation heat recovery (%)	70	80	70	70	80

Corresponding Heating energy demand ($kWh/m^2 \cdot yr$)						
	Renovation: Package I			**Renovation: Package II**		
Cohort	**Single**	**Detached**	**Blocks**	**Single**	**Detached**	**Blocks**
< 1950	55	50	45	24	21	17
1950 - 1970	50	46	35	22	18	12
1971 - 1980	55	39	31	25	15	10
1981 - 1990	44	33	30	19	12	9
1991 - 2010	42	49	30	17	23	10
	Current building code (TEK-10)			**Passive houses**		
2011 - 2100	45	54	28	23	33	11

Table 3: Scenario overview and carbon footprint. The numbers show the sectoral carbon footprint in terms of the 2000 emission baseline (8.7 Mt/yr) in %.

Scenario number	**Description**	**2011**	**2020**	**2030**	**2040**	**2050**	**2060**
1	**BASELINE: 0.6% demolition and 0.5% renovation, medium growth**	**102**	**103**	**100**	**95**	**92**	**90**
2	Baseline without optimization algorithm	103	107	105	101	**98**	95
3	Baseline without demolition and renovation, medium growth	96	103	105	106	**108**	110
4	Sensitivity α: increased from 0% to 90%	102	103	100	94	**90**	88
5	Sensitivity population: low SSB estimate for population	102	98	92	84	**76**	70
6	Sensitivity PpD: progressive linear scaling to 115 % in 2060	100	99	94	87	**82**	78
7	Sensitivity UFApD: progressive linear scaling to 85% in 2060	100	99	93	86	**80**	76
8	Sensitivity Type: share of single family houses reduced by 50%	102	103	101	96	**92**	91
9	Sensitivity Demolition: demolition rate increased to 2%	113	111	102	97	**72**	74
10	Sensitivity Renovation: renovation rate increased to 2%	105	101	91	84	**72**	74
11	Sensitivity building code: share of TEK-10 buildings reduced to 0% by 2020	102	105	100	94	**89**	86
12	Sensitivity heating system: Heating system shares increased to High scenario	102	100	94	87	**80**	76
13	Sensitivity DHW: energy demand for DHW reduced by 50%, r >=3 only	102	102	97	91	**86**	83
14	Sensitivity Appliances: energy demand for appliances reduced by 50%	102	102	97	91	**86**	83
15	Combine scenarios 9 and 11	113	114	102	94	**65**	66
16	Combine scenarios 10 and 11	105	103	90	82	**69**	70
17	**Transformation Bottom (TB): Combine 16 and 4**	**106**	**102**	**87**	**77**	**62**	**63**
18	TB plus progressive reduction of UFApD down to 85%	104	97	80	68	**51**	51
19	TB plus progressive increase of PpD up to 115%	104	98	80	69	**52**	52
20	TB plus low SSB estimate for population	106	96	78	66	**49**	49
21	TB plus high SSB estimate for population	106	108	102	98	**86**	93
22	**Combine scenarios 18 and 19**	**101**	**93**	**75**	**63**	**45**	**45**
23	TB plus increases share of heat pumps and other alt. heating	106	98	79	66	**49**	51
24	Scenario 23 plus decreased energy demand for DHW	105	97	76	61	**45**	46
25	Scenario 24 plus decreased demand from appliances	105	93	69	51	**33**	34
26	**BOTTOM LINE: Combine scenarios 22 and 25**	**101**	**86**	**61**	**43**	**23**	**23**

Coloring: reduction in % compared to the 2000 reference value of 8.7 Mt/yr

< 0%	**11-20%**	**34-50%**
0-10%	**21-33%**	**>50%**

Table 4: Total sectoral energy demand (a) and electricity saved by households (b), 2011…2060, by scenario.

(a)	**Total sectoral energy demand in TWh/yr (Base value 2000: 45 TWh/yr)**						**(b)**	**Electricity saved compared to 2000 level (34 TWh/yr) in TWh/yr**					
Scenario number	**2011**	**2020**	**2030**	**2040**	**2050**	**2060**		**2011**	**2020**	**2030**	**2040**	**2050**	**2060**
1	**47**	**46**	**46**	**43**	**42**	**40**		**-2**	**-1**	**-1**	**0**	**2**	**3**
2	47	48	48	47	45	43		-2	-3	-3	-2	**-1**	1
3	46	50	52	53	54	55		-2	-4	-7	-8	**-9**	-10
4	47	46	45	43	40	39		-1	-1	-1	1	**3**	4
5	47	45	43	40	36	33		-2	-1	1	3	**6**	8
6	46	45	44	41	38	36		-1	-1	0	2	**4**	6
7	46	45	43	40	37	35		-1	-1	0	2	**5**	6
8	47	46	46	43	41	40		-2	-1	-1	0	**2**	3
9	47	44	40	37	35	36		-1	2	5	7	**7**	6
10	46	43	39	36	35	36		-1	2	5	7	**7**	6
11	47	46	45	42	40	38		-2	-1	0	2	**3**	5
12	46	45	43	40	37	36		-1	0	2	4	**7**	9
13	46	45	44	41	39	37		-1	-1	0	2	**4**	5
14	46	46	44	42	39	38		-1	0	1	3	**5**	6
15	47	44	39	34	31	32		-1	2	6	9	**9**	8
16	46	43	38	35	33	34		-1	2	6	8	**8**	7
17	**46**	**42**	**36**	**31**	**29**	**30**		**-1**	**3**	**7**	**11**	**10**	**10**
18	46	41	34	29	25	25		-1	3	8	12	**13**	13
19	46	41	34	29	26	26		-1	3	8	12	**13**	13
20	46	41	34	28	24	24		-1	3	8	12	**14**	14
21	46	43	39	37	38	41		-1	2	6	8	**5**	2
22	**46**	**40**	**33**	**27**	**23**	**23**		**-1**	**4**	**9**	**13**	**15**	**15**
23	46	41	33	27	25	26		-1	5	11	16	**16**	15
24	46	40	31	24	22	22		-1	5	12	17	**17**	17
25	46	38	28	20	17	17		0	7	15	22	**23**	23
26	**45**	**37**	**26**	**18**	**13**	**13**		**0**	**7**	**15**	**22**	**25**	**25**

Coloring: reduction compared to the 2000 reference value of 34 TWh/yr

>0	**6...10**	**16...20**
0...5 TWh/yr	**11...15**	**>20 TWh/yr**

FIGURES

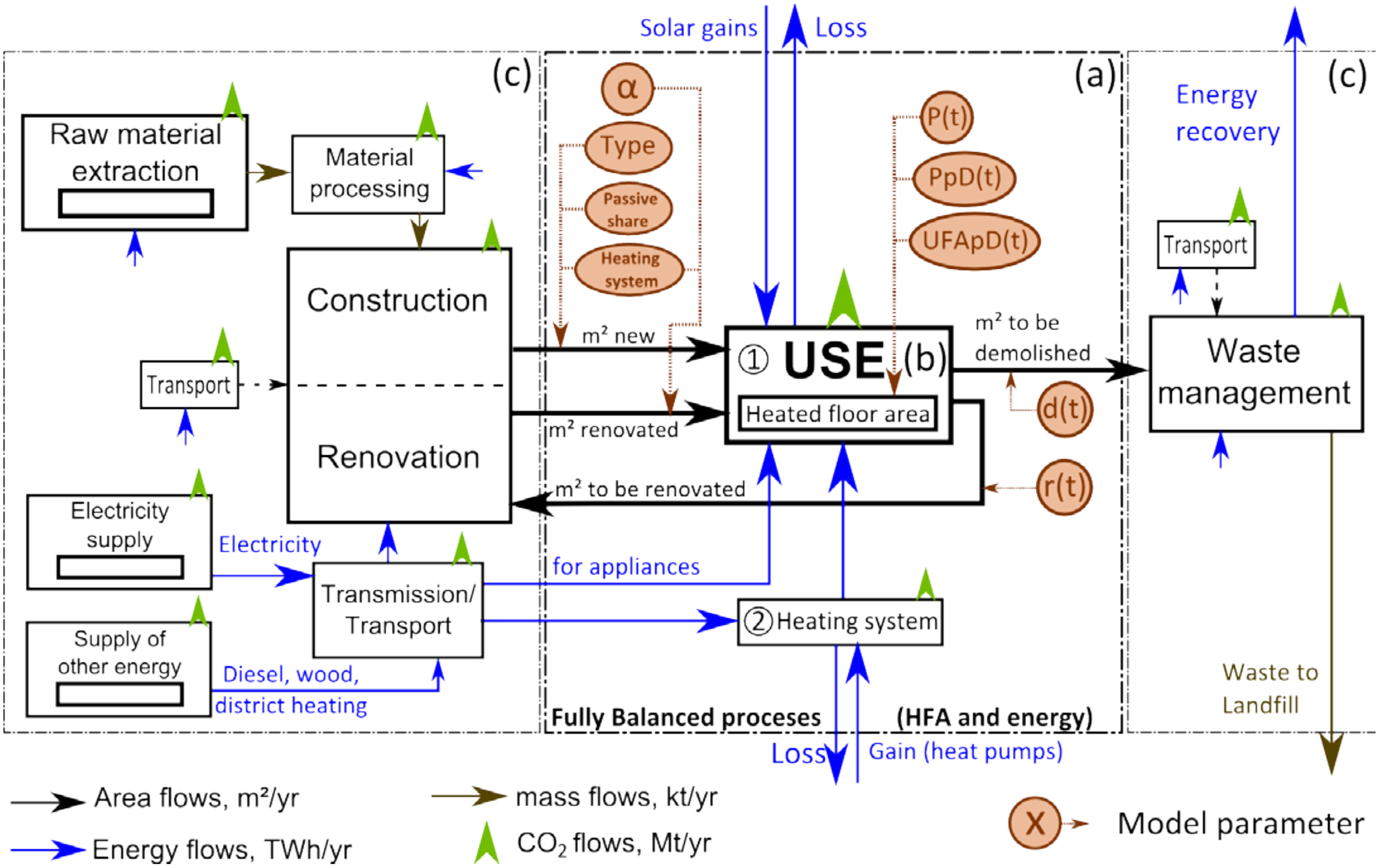

Figure 1. System definition

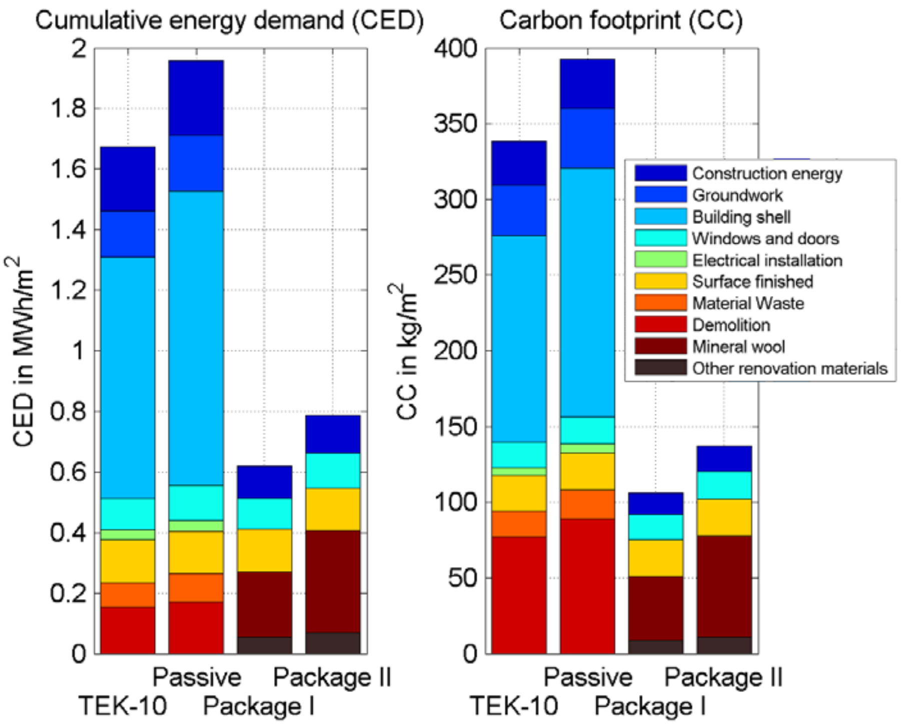

Figure 2. Cumulative energy demand and carbon footprint of new construction and renovation according to the system part (c) in Fig. 1.

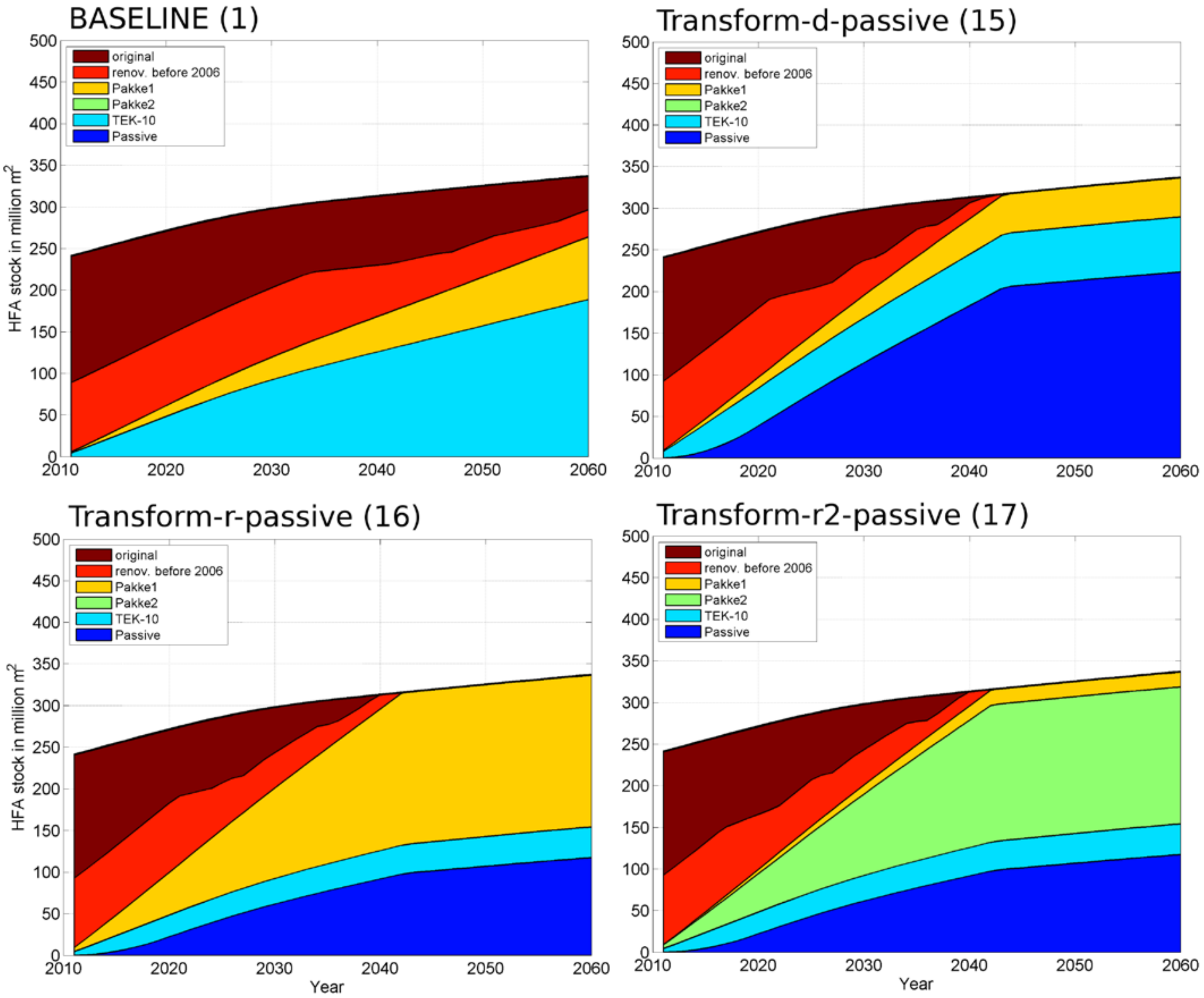

Figure 3. HFA by renovation level for selected transformation scenarios, 2011-2060.

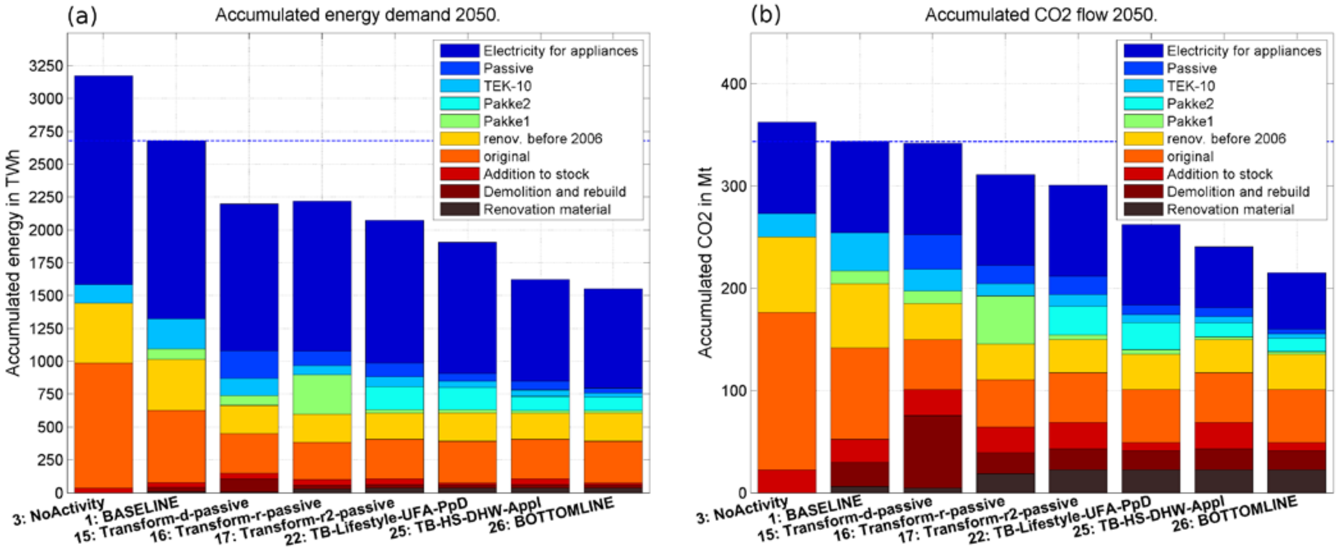

Figure 4. Accumulated total energy consumption and CO_2 emissions for the period 2011- 2050.