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Climate target fulfilment in scenarios for a sustainable Swedish built environment beyond growth

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ARTICLE INFO

Keywords:

Backcasting scenarios
Greenhouse gas emissions
Built environment
Embodied emissions
Operational energy use

ABSTRACT

This paper explores opportunities for the built environment to fulfill a far-reaching greenhouse gas (GHG) emission target in Sweden in 2050, in a context of low or no economic growth. A spreadsheet model was created, allowing for a quantitative estimation of GHG emissions and operational energy use for the built environment. Building on previous qualitative descriptions of four future scenarios, the model was run to investigate what reaching the target would require in each scenario. The results can inform policy discussions and provide insights on what strategies appear to be significant, and what they entail in terms of operational energy use in 2050 and cumulated embodied emissions from investments prior to 2050. It thus appears particularly important to decarbonate the energy mix and reduce floor areas through space sharing and optimization. When emission factors for heat and electricity are very low, the climate impact of construction materials becomes an important issue, on par with operational energy use, and strategies aimed at improving construction processes or avoiding new construction gain relevance. Extensive renovation for energy efficiency exhibits in this case a tradeoff between embodied emissions from prior investments and energy use, as decreasing one means increasing the other.

1. Introduction and aim of the study

Imagining future societies is both a relevant issue for policy and planning and a key research task, requiring explorative work on how societies can keep within planetary boundaries (Rockström et al., 2009; Steffen et al., 2015) and achieve a development that is both environmentally safe and socially just (Raworth 2012). Researchers and planners need to highlight potential conflicts between different sustainability goals, as well as with respect to currently prevalent assumptions and structures. There is increasing criticism towards the formulation of economic growth as a societal goal in itself (D'Alisa, Demaria, & Kallis, 2014), illustrated in the UN Sustainable Development Goals sub-target to “Sustain per capita economic growth in accordance with national circumstances...” (UN, 2015). It has been claimed that continued economic growth in high-consumption societies conflicts with environmental and social sustainability goals (Anderson & Bows, 2011; Oliver-Solà, 2010), implying that there is a need to plan for scenarios that outline a just development within ecological limits, but where growth is no longer a given.

The design, construction and use of the built environment shape and are shaped by both people's everyday life and the general organization of society. In relation to the range of transitions needed in all sectors of society, there is therefore a need to explore what our built environment could look like in sustainable future societies, and how the building sector could be part in achieving sustainability beyond contemporary models of development. Widespread discourses revolving around circular or collaborative economy

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<https://doi.org/10.1016/j.futures.2017.12.001>

Received 20 April 2017; Received in revised form 24 October 2017; Accepted 10 December 2017
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call for innovative solutions linked to how resources, spaces and infrastructures are distributed, maintained and used. Similarly, community-initiated alternatives such as eco-villages or co-housing are commonly put forward as providing new or re-invented opportunities for low-impact living (Chatterton, 2013; Seyfang, 2010). Yet, limited quantitative studies exist on the potential of such solutions to contribute to more radical transitions (Xue, 2014).

The Swedish research program “Beyond GDP growth – Scenarios for sustainable building and planning¹”; was initiated in 2014 to explore challenges and potentials for fulfilling far-reaching sustainability targets, in a future where GDP growth is not taken for granted (Svenfelt et al., 2015). The core of the research program is the development of four normative backcasting scenarios examining radically different visions of how to fulfill the targets in 2050: 1) Circular economy in the welfare state, 2) Automation for quality of life, 3) Local self-sufficiency, and 4) Collaborative economy (Svenfelt et al., 2015).

The aim of this study is to further detail these backcasting scenarios with regards to the built environment, focusing especially on how a low greenhouse gas (GHG) emission level could be reached in Sweden in 2050, including investigating cumulative embodied emissions up to 2050.

The article addresses the following research questions:

- Under what conditions can the development of the Swedish built environment until 2050 be compatible with keeping global warming below +1,5 °C?
- What key improvement strategies are the most impactful in terms of GHG emissions and operational energy use in the built environment?
- What potential conflicts and trade-offs between the envisioned strategies can be identified, and what aspects seem to require particular attention from building sector stakeholders?

2. Background

2.1. The “Beyond GDP growth” program targets and scenarios

The Beyond GDP Growth research program considers four far-reaching sustainability targets (Fauré, Svenfelt, Finnveden, & Hornborg, 2016; Svenfelt et al., 2015). Two qualitative social targets relate to an equal distribution of power, and a fair and sufficient access to resources and welfare. Two environmental targets, related to land use and GHG emissions, were set in a more quantitative way by establishing limits per capita following a consumption perspective:

- GHG emissions are to decrease to 820 kgCO₂e/(person.year) by 2050. This level would allow limiting global warming below 1,5 °C with a 50% certainty (Fauré et al., 2016) and corresponds to a 92% decrease compared to current Swedish emission levels (Swedish Environmental Protection Agency, 2010).
- Land area used for final consumption must be reduced below 1,24 global hectares per capita to avoid overshooting global bio-capacity. This corresponds to a decrease of about 65% compared to current Swedish per capita land use (Fauré et al., 2016).

This study focuses primarily on the GHG emission target, but briefly discusses implications for land use as well.

Four scenarios were developed to describe Swedish society in 2050, with a focus on the operationalization of the four above-mentioned targets (Svenfelt et al., 2015). Backcasting scenarios are not to be seen as likely futures, but rather identify different opportunities to reach the targets, based on contemporary discourses on strategies for solving sustainability challenges (Dreborg, 1996; Robinson, 1990). Moreover, contrasting with current paradigms, they are all set in a context of shifting the dominant economic activity in a low or no GDP growth society, with a fossil- and nuclear-free energy mix. The four scenarios are:

- **Circular economy in the welfare state:** This scenario assumes a continuation of current Swedish societal dynamics, where the state holds a strong role, along with larger corporations. Improvements towards sustainability rely mostly on a service-oriented economy and a strong focus on material efficiency: products and buildings are designed to be reused, repaired and recycled, and material and energy flows are circular. Activity is centralized in large metropolitan areas.
- **Automation for quality of life:** This scenario assumes omnipresent high technology and robotization. Once the necessary investments in technology have been made, economic growth is voluntarily limited and the focus switches to well-being and resource repartition. Widespread automation drastically decreases paid work, together with levels of consumption. Dense clusters of buildings in existing as well as completely new cities allow for an easy automated management of heating, ventilation, water flows, etc. The electricity demand is high, but so is resource efficiency.
- **Local self-sufficiency:** This scenario assumes a shift of power from national and global levels to the regional and local level, with an emphasis on relocalization and reruralisation. Society is decentralized and organized around smaller self-sufficient communities. Levels of technology and consumption are lower than in other scenarios, based to a high extent on local materials and preconditions. Life is organized around the local supply of food and goods for the community.
- **Collaborative economy:** This scenario assumes a successful cooperation towards sustainable development at local, national and international levels. Goods and services are shared and society revolves around collaborative lifestyles (co-housing, sharing of

¹ <http://www.bortombnptillvaxt.se/english/startpage>.

Table 1

Review of backcasting or other future studies of relevance to the present study.

Study	Summary	Key differences with the present study
(Fujino et al., 2008)	Investigates the possibility of a 70% reduction in GHG emissions in Japan by 2050 compared to 1990 levels	Overarching input-output equilibrium model. Embodied GHG emissions from necessary investments before 2050 are not considered. Less ambitious target. Closer to current paradigm: continued growth of GDP and use of fossil fuels and nuclear power
(Gomi, Ochi, & Matsuoka, 2011)	Backcasting case study for a 45% reduction in GHG emissions for the city of Kyoto by 2050	Overarching model to paint a broad, simplified picture rather than investigating a particular sector. Local scale. Less ambitious target. Closer to current paradigm, no radical societal change. Focus: developing a roadmap to 2050 rather than describing society in 2050.
(Ashina et al., 2010)	Roadmap to a low-carbon society in Japan in 2050, with a 80% GHG emission reduction target	Model focusing on cost minimization and the penetration of new technologies. Less ambitious target. Closer to current paradigm in terms of lifestyles and energy supply (fossil and nuclear fuels are still used). Focus: develop a roadmap to 2050 rather than describing society in 2050.
(Strachan, Pye, & Hughes, 2008)	Pathways towards a low carbon society in the UK based on a model of the energy supply and demand.	Scenario forecasts based on current trends, no common normative goal between scenarios. Models GDP, energy supply and demand
(Anderson et al., 2008)	Backcasting study for a low-carbon society in the UK with a 60% GHG emission reduction target	Focus on economic profitability, carbon taxes and emission credits, using a neoclassical economic model. Overarching approach, not specific to the built environment. Less ambitious target.
(Doyle & Davies, 2013)	Backcasting study about sustainable practices related to the consumption of Irish households, and in particular the most promising practices for heating.	Closer to current paradigm in terms of lifestyles and energy supply (fossil and nuclear fuels are still used, all scenarios assume an increase in GDP and energy use)
(Svenfelt, Engstrom, & Svane, 2011)	Backcasting study on a 50% reduction in energy use in the building sector by 2050	Narrower scope: only focuses on heating Qualitative study: strategies are assessed on abstract scales corresponding to new economy indicators Narrower scope: operational energy use, thus excluding construction and renovation. The focus is not on physical changes for the built environment, but rather on a qualitative analysis of behavioral changes and policy measures necessary to accomplish the target. Focus on pathways rather than a depiction of the situation in 2050.
(Åkerman, Isaksson, Johansson, & Hedberg, 2007)	Backcasting study of an 87% reduction in per capita GHG emissions from the Swedish energy and transport systems by 2050.	More overarching approach based on energy mixes and broad indicators of “change in activity” concerning distance traveled per person, energy use for heating, industrial activity, etc. Production perspective. Scenarios are distinguished by time use patterns (fast or slow lifestyles), how much biomass is used, and whether the consumption of material goods or experiences is prioritized. Embodied GHG emissions are not considered.
(Höjer, Gullberg, & Pettersson, 2011)	Backcasting study of a 60% reduction in per capita energy use by 2050, focused on the Stockholm region.	Focus on energy use, with a less ambitious target than the present study's. More overarching conceptual scope and more restricted spatial scope (the Stockholm region). Scenarios are less radical and distinguished by time use patterns (fast or slow lifestyles) and whether urban development is monocentric, polycentric or decentralized.

space, vehicles, appliances, knowledge, etc.). Collaborative clusters of buildings are located in small- to medium-sized towns.

2.2. Previous backcasting studies of target fulfilment in the built environment

The backcasting approach has been used since the late 1970s in Sweden as a tool for planners to explore a broader scope of solutions compared to forecasting. Since it is explicitly detached from current trends, it is relevant when these very trends are part of the problem, and when major changes are required (Dreborg, 1996). A number of backcasting or other future studies have targeted energy or GHG emissions reductions at an overarching level or for the built environment in particular. A review of such studies of relevance is summarized in Table 1.

To summarize, numerous future studies have dealt with the pressing issue of reducing energy use and/or GHG emissions, for the built environment or at an overarching societal scale. However, to the authors' knowledge:

- No published quantitative backcasting study considers both future GHG emissions and operational energy demand, and cumulative embodied emissions linked to target fulfilment prior to the target year.
- No published quantitative backcasting study explores a context beyond growth with a nuclear- and fossil-free energy mix. The present study assumes more radical changes compared to the current paradigm.

Table 2

System boundaries for the quantitative modelling of GHG emissions and energy use associated with the built environment.

	Aspects included	Notable aspects excluded
Energy supply	Construction and operation of power and heat plants, both centralized (district heating, dams, etc.) and off-grid systems (small-scale photovoltaics, etc.).	Production of power lines, hot water pipes, and the related infrastructure. Changes in distribution losses, possible economies of scale in scenarios with large centralized plants.
Buildings (inventory coverage)	All residential buildings Work spaces for the tertiary sector (services, retail, entertainment, etc.). To simplify, services are all assumed to be office jobs. ^a	Buildings and infrastructure related to the primary and secondary sectors (factories, mines, farms, etc.) Transport infrastructure (roads, railways, etc.)
Construction of new buildings	Emissions associated with production of materials for construction, transport to construction site and on-site construction processes.	
Renovation of buildings	Production of construction materials for renovation to higher energy performance.	Emissions associated with retrofitting and interior design. Renovation processes other than the production of materials (use of machinery, etc.). Demolition and waste management.
Operational energy use	Space and water heating in all buildings. Property electricity in multi-family buildings and offices (pumps, elevators, etc.) User electricity in all buildings (lighting and household or work-related appliances.)	Change in time use patterns (spending more or less time at work, eating more or less out, etc.), new forms of jobs and lifestyles, etc.

^a The surface of workspaces is underestimated since supermarkets, parking lots, etc. have a much higher surface area per employee than offices.

Most similar backcasting studies remain qualitative only. The present study builds on the idea that elaborating on quantitative modelling can stimulate discussions and provide useful insight to revise backcasting scenarios, assessing them from a new angle.

3. Methodology

A spreadsheet model was developed to calculate GHG emissions for the built environment in the four scenarios, as well as operational energy demand in 2050 and cumulative embodied GHG emissions from investments in buildings from 2020 to 2050. The procedure of the study is presented in the subsequent sections, which highlight key methodological points for each step.

3.1. Scope and system boundaries

The present study builds upon qualitative descriptions of the Beyond GDP growth scenarios to investigate their implications in a more quantitative manner, with a specific focus on the built environment (i.e. without considering scenario aspects related to changes in employment, consumption of goods, etc.). Therefore, a bottom-up approach was used in order to concretize scenario assumptions, making it easier to emphasize particular changes in e.g. materials types or floor areas compared to a more overarching top-down approach. The aspects covered by the model are described in Table 2. Certain sources of emissions have been overlooked, either because their impact was considered insignificant (e.g. decommission of PV power plants), or because of the difficulty to model them (e.g. emissions from fit-out and repurposing works). The study remains self-enclosed: results from one iteration of the model are only compared with results from other iterations of the model, obtained using the same method and within the same system boundaries. The approach is only meant to be valid to discuss scenarios in relation to each other, not in relation to present or future external indicators based on another scope and methodology.

3.2. Parameters used in the model

The aspects in Table 2 are modelled using about 70 parameters to calculate GHG emissions related to the built environment (illustrated in Fig. 1 and further in appendix, Tables A1 and A2). The parameters selected emphasize remarkable features of each Beyond GDP Growth backcasting scenario (e.g. reduced indoors temperatures or technological improvement), features that shape how buildings are designed and used (e.g. floor area), and/or features that impact greenhouse gases emissions (e.g. electricity and heat mixes). Even though GHG emissions in 2050 are calculated by the model, they were fixed at a certain quota in all scenarios. The study investigated how parameters can be adjusted empirically to reach this quota. Therefore, the list of parameters used is an input of the model, but an output of the study.

GHG emissions for the built environment in 2050 are the sum of emissions due to operational energy use (heat and electricity) and emissions from the construction and renovation of buildings during this year. Operational energy use is calculated based on assumptions about floor areas per person in dwellings and offices, energy performance, use of appliances per type of household, and electricity use for lighting and property electricity. Emissions from construction and renovation are based on the total floor area in dwellings and offices in 2050 and the share of it that is new, moderately or extensively renovated, and on assumptions about technological improvements and materials used in construction. Cumulative embodied emissions between 2020 and 2050 are the sum of emissions from construction and renovation of dwellings, offices, and new power plants for each year from 2020 to 2050.

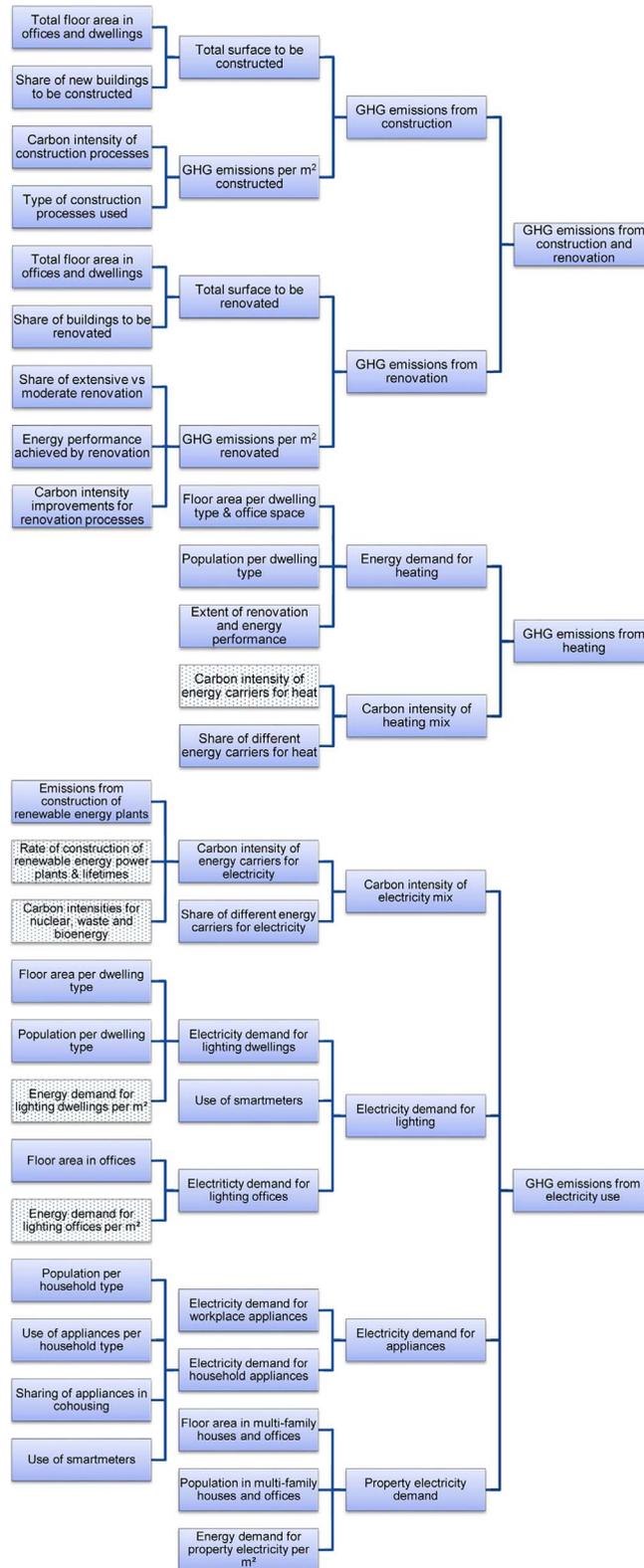


Fig. 1. Simplified process chart of the model. Dotted cells indicate parameters that are kept constant between scenarios

3.3. Emission sub-quota for the built environment

The Beyond GDP growth project's GHG emission quota corresponds to a reduction of emissions from Swedish consumption as a whole of slightly over 92%, but has yet to be further subdivided between different sectors (transports, the built environment, goods and services, etc.). Previous input-output studies have estimated the share of GHG emissions from Swedish consumption attributed to the built environment to about 20–30% (Swedish Environmental Protection Agency, 2010; Toller et al., 2011). However, the present study uses a different method (based on process LCA data) and a more restrictive scope. To ensure consistency, the approach chosen to set a sub-quota for the built environment has been to run the model with parameter assumptions close to the present situation, to get an order of magnitude of current emissions within our scope. A 92% reduction was then applied to this rough estimate to obtain a sub-quota for 2050, assuming that the proportional decrease in emissions for the built environment would be equal to the overall decrease for Swedish consumption in all scenarios. The built environment could be expected to represent a different share of total emissions depending on the scenario, but the same sub-quota was set for all scenarios to simplify comparison. The 92% reduction is also in line with reductions of 90% for the built environment suggested in the European and Swedish Roadmaps for a low-carbon society (European Commission, 2011; Swedish Environmental Protection Agency, 2012). This approach yielded a sub-target of 100 kgCO_{2e}/(person.year) for the built environment within the previously mentioned system boundaries.

3.4. Parameter assumptions for the four scenarios investigated

The parameter assumptions used in the four runs of the model (summarized in appendix, Table A1) were based on an interpretation of the qualitative scenario descriptions (Svenfelt et al., 2015), relating to the built environment as presented in Table 3. Assumptions in the respective scenarios convey different strands of discourse and literature on transformative processes and solutions for a future sustainable built environment, and were complemented by discussions with an extended expert group. A literature review was also performed to speculate about achievable future values for the model parameters (in particular regarding carbon intensities and technological improvements). The economic feasibility of investments needed to achieve the respective development trajectories was out of scope. Instead, the assumptions chosen for different parameters are explorative, to provide a comparison of what the different scenarios entail, offering a basis for further discussion.

The intention was thus to come up with sets of consistent assumptions illustrating various strategies to achieve the GHG emission target, and then to discuss the challenges these strategies might raise. This was done via an iterative process, running the model numerous times and adjusting parameter assumptions until the desired value for emissions in 2050 is reached. Before 2050, the diffusion of technologies (e.g. renewable electricity production or new construction materials) is assumed to follow an S-shaped logistic curve; population grows according to a fixed rate; and all other parameters are assumed to follow a linear evolution (methodological details are provided in the Supplementary material).

To simplify and allow for an easier comparison between the scenarios, the assumptions for a number of parameters (summarized in appendix, Table A2) are kept constant, for three main reasons:

- there is nothing in the scenarios clearly motivating differentiation
- changing the parameter has a very limited impact on the calculated results, or
- changing the parameter would introduce a bias that can't be corrected within the scope of the model²

4. Results & discussion

This section presents the results of the modelling exercise, and how they can be used to inform the discussion of the four backcasting scenarios.

4.1. Emission target fulfilment

Fig. 2 shows a breakdown of the emission sub-quota in 2050. These four set-ups are based on the scenario assumptions outlined in section 3.4 which illustrate potential strategies for the built environment to keep within the sub-quota. The results and the table of parameters (in Appendix A) highlight how far the built environment needs to be modified to reach ambitious targets, and what aspects are significant in that regard.

The results indicate that a low emission level of 100 kgCO_{2e}/(person.year) for the built environment could be reached in 2050 using a broad variety of strategies. No activity represents an overwhelming share of the emissions. Renovation and construction constitute proportionally large shares compared to today, even though heating is still the main contributor to emissions (Boverket, 2014). Emissions linked to electricity use are low, due to the fact that the fully renewable electricity mix has a low emission factor.

In order to find out which changes are the most impactful and what parameters are critical for the target to be met, a sensitivity analysis was performed (results are provided in appendix, Table A3). It investigated the effects of a 1% change in various parameters

² For instance, the share of the population working in the tertiary sector of the economy was kept constant because other sectors are out of scope. Assuming that a higher share of the population would work in the primary and secondary sectors would artificially drive down the emission level, because GHG emissions from their work would be invisible.

Table 3
Main scenario characteristics related to the present study.

Characteristic	Circular Economy	Self sufficiency	Automation	Collaborative Economy
Energy mix	High use of waste heat and biofuels. Development of tidal power. Almost no incineration of non-biogenic waste.	Use of existing and repurposed technologies, such as heat pumps, small-scale biofuel burners and complementary solar heating on rooftops. Small-scale hydropower and PV panels produced in Sweden.	Waste incineration is still present. Large use of solar power, with improved PV technologies (thin film, quantum dot photovoltaics, etc.)	Large share of heat pumps. Low waste incineration due to reduced waste flows, but collaboration across industries/sectors to promote the use of waste heat. Large development of wind and solar power at a regional level.
Households and dwellings	Continued demographic development towards many single person households. Most dwellings are apartments located in dense cities.	People often live with or in close vicinity to relatives, parents and friends as an extended family. Spread-out development in the suburbs and countryside, with low-rise houses.	Large variety in household structures. Most people live in very small but well-optimized apartments in dense metropolises.	Close to the current structure of households, yet organized in a more collaborative way. Cohousing is broadly adopted: space and appliances are shared to a large extent.
Electricity use	Decreased use of appliances due to high price of electricity. Moderate use of smart-meters to manage and reduce electricity use.	Very large decrease in use of electricity for ICT and entertainment due to changes in both everyday practices and infrastructure.	Omnipresent technology. Electricity use for ICT, entertainment and home automation is high. Smart-meters are used extensively.	Slight decrease in use of appliances due to behavioral changes. Large savings achieved in cohousing communities due to sharing and use of smart-meters.
Thermal performance and renovation	National renovation plan: improvements in thermal performance and retrofits of older buildings to avoid new construction	Little improvement in thermal performance due to a lack of strong actor promoting renovation and limited technology. Instead, people adapt their practices (space heating, clothing etc.).	Advanced processes in construction and renovation allow for an extremely low demand for heating.	Retrofits are encouraged, energy renovation is common but moderate. Space sharing in dwellings and offices reduces the area to be built and heated.
Construction processes	High reuse and recycling of construction materials and technological improvements lead to large reductions in carbon intensity. Concrete construction remains dominant but can use innovative formulations for materials and processes.	Construction revolves mostly around locally-sourced materials such as wood, clay and straw bale. There is little efficiency improvement for construction processes.	Most buildings are built using innovative, high-tech processes such as 3D-printing or new materials such as low-emission concrete. Savings are mostly due to improvements in process efficiencies, not necessarily improved recycling.	Construction with mostly local or regional materials, adapted to users' demands. Wood construction is the most common, but all processes are used to some extent.

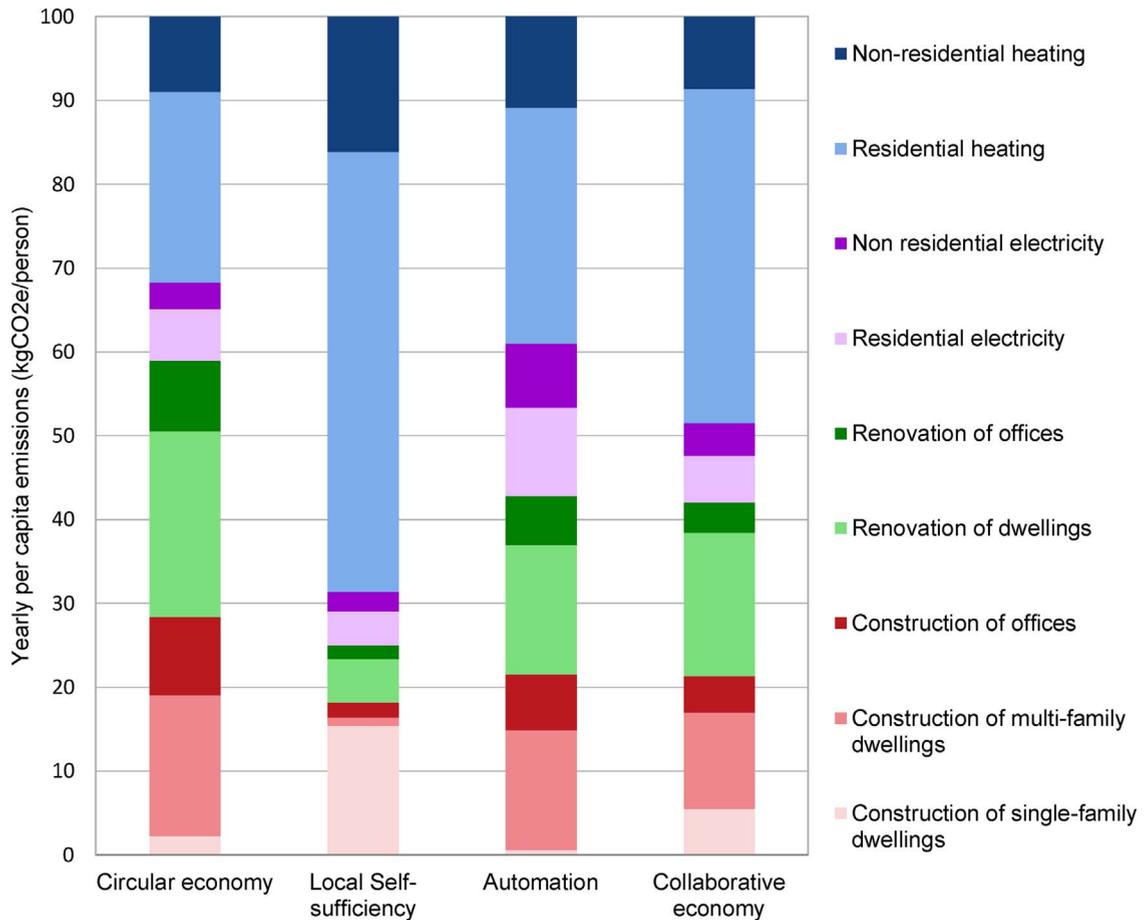


Fig. 2. Breakdown of yearly per capita emission quota in 2050 attributed to the built environment.

compared to scenario values for each scenario. The analysis focused on parameters that were central to scenario discussions and/or commonly discussed within a low-impact transition narrative. Insights gained from the model run and the sensitivity analysis are discussed below.

Significant strategies for staying within the emissions quota, no matter the scenario, include decarbonating the energy mix, decreasing floor area per person, improving construction processes and retrofitting existing buildings instead of constructing new ones.

The model shows that a pre-condition for target fulfilment in all scenarios is a nearly fossil-free energy supply in 2050.³ This is a considerable challenge in itself, and is mostly achieved through an extensive use of biofuels and hydropower in all scenarios, although the shares of different energy carriers vary. If the energy mix is not thoroughly decarbonated, the target is unachievable without dramatic restrictions in floor area, technological or lifestyle changes, etc. For example, the Automation scenario assumes a higher share of non-biogenic waste incineration. The resulting higher emission factors for heating and electricity are compensated by particularly small and highly energy-efficient dwellings to reach the target. Decarbonating the energy mix is therefore a key strategy for all scenarios, but in particular for scenarios with low energy performance and/or high floor areas since they require more heating. A particularly crucial aspect in that regard is the form biomass incineration will take in each scenario: carbon intensities can be considerably different for byproducts of forestry, trees cut down for direct energy recovery, algal cultures, etc. This issue is discussed further in section 4.3.

However, it should be noted that a low-carbon energy mix is required but not sufficient. The various scenarios still require large changes in both behavior and technology for target fulfilment, such as considerably reduced carbon intensities for construction due to increased recycling in Circular Economy, extremely efficient construction and renovation processes and small floor areas in Automation, a ruling out of concrete construction and a substantial change in heating practices in Local Self-Sufficiency; or the sharing of space and appliances in Collaborative Economy.

³ The only remaining fossil fuel is non-organic waste.

Table 4
Modelled floor areas in dwellings and workplaces in the studied scenarios and current values.

	Current Swedish average	Circular Economy	Local Self-sufficiency	Automation	Collaborative Economy
Average floor area per person in dwellings (m ²)	42	31	38	20	26
Average floor area per person in workplaces (m ²)	20–25	15	20 effective 14 attributed	10	14 effective 7 attributed ^a

^a Effective office space refers to the working space an employee will actually enjoy when they work. Attributed office space refers to the total office space divided by the number of employees. These numbers can be different due to remote working: for instance, if two employees share the same 20 m² office, but work remotely half of the time respectively, their effective office space is 20 m² and their attributed office space is 10 m².

Floor area per person in dwellings and offices appears to be the most sensitive parameter. The average floor area in each scenario is indicated in Table 4 below.

Floor area per person is influenced both by the size of dwellings and by the type of dwelling people live in. Thus, it is the lowest in Automation due to the assumptions of a considerable space optimization and a widespread adoption of compact dwellings in multifamily buildings. In Collaborative Economy, floor area is rather low as well, but this is mostly due to the sharing of space, for example in cohousing schemes. That is, dwellings are not significantly smaller than today, but they are shared to a greater extent.

The construction of new dwellings and offices accounts for about 20% of GHG emissions from the built environment in all scenarios. Each scenario uses different strategies to mitigate these emissions, either by using cleaner construction processes or by avoiding new construction altogether. In the Local Self-sufficiency and Circular Economy scenarios, and to a lesser extent the Collaborative Economy scenario, construction is avoided by promoting retrofitting and reconfiguration of existing buildings. Additionally, space sharing and optimization directly impact the surface of new buildings to be constructed. In addition, construction processes can be modified to reduce emissions per square meter constructed. This can be achieved by incremental improvements, such as increasing material and energy efficiency through better technology, or improving recycling (in particular in the Circular Economy scenario). Such improvements at the scale of the construction industry also impact emissions from the construction of wind-, tidal- and hydropower plants since they require large amounts of steel and concrete. More radical changes can also be considered, such as switching to other materials, e.g. wood and straw bale in the Local Self-Sufficiency scenario, or innovative new materials for e.g. 3D-printing and prefabrication in the Automation scenario.

It should be noted that benefits from reconfiguring older buildings in place of new construction in some scenarios are overestimated, as emissions from the reconfigurations themselves aren't modeled. It is important to keep in mind that reconfigurations can represent important sources of GHG emissions, especially in scenarios where dwellings require extensive modifications (e.g. space optimization and broad implementation of smart metering and connected items in Automation, reconfiguration for space sharing in Collaborative Economy). For example, an extensive retrofit of an office building yielded emissions of around 60 kgCO₂e/m² (Liljenström and Malmqvist, 2016). An estimation for the Collaborative Economy scenario assuming that half the building stock would be subject to one such retrofitting before 2050 shows that the corresponding emissions could be on par with total emissions from energy-efficiency renovations (this result depends largely on the extent of retrofitting and energy renovation and can therefore not be generalized).

4.2. Operational energy demand and cumulative emissions

4.2.1. Operational energy demand in 2050

The results and sensitivity analysis suggest that energy-efficiency renovation can be contra-productive when it is carried out extensively. Embodied emissions from extensive renovation measures (requiring significant works) can outweigh benefits from reduced operational energy use if (and only if) the energy mix is thoroughly decarbonated. GHG emissions are thus to some extent decoupled from energy use, and the emission sub-quota can be reached with varying levels of energy use. It is therefore of interest to separately consider operational energy demand in each scenario, as illustrated in Fig. 3.

The final energy demand for the built environment is significantly lower than today in all scenarios, especially due to a reduced energy use for heating. It is the highest in the modelled Local Self-sufficiency scenario, which assumes limited improvements in energy renovation and low-energy new build (being a scenario with a low availability of funds and technological limitations). This lower energy performance (95 kWh/m² HFA on average compared to between 32 and 58 kWh/m² HFA for other scenarios and 130 kWh/m² for present buildings), coupled with a high floor area per person, leads to a significantly higher energy demand for heating. This scenario however assumes a change in attitudes regarding thermal comfort and heating practices, which compensates to some extent for the poorer energy performance. The energy demand in Circular Economy is also fairly high, as little effort is put into optimizing space or decreasing the use of appliances in this scenario. On the other hand, the energy demand in the Automation

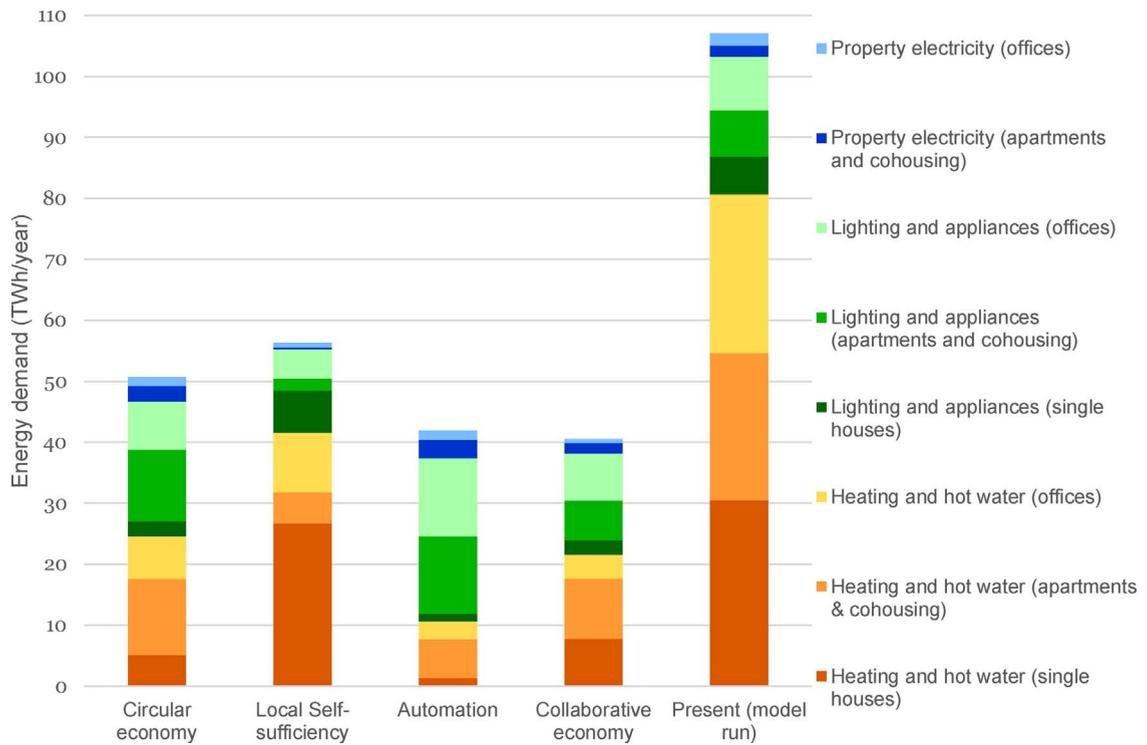


Fig. 3. Modelled operational energy demand in Swedish buildings in 2050.

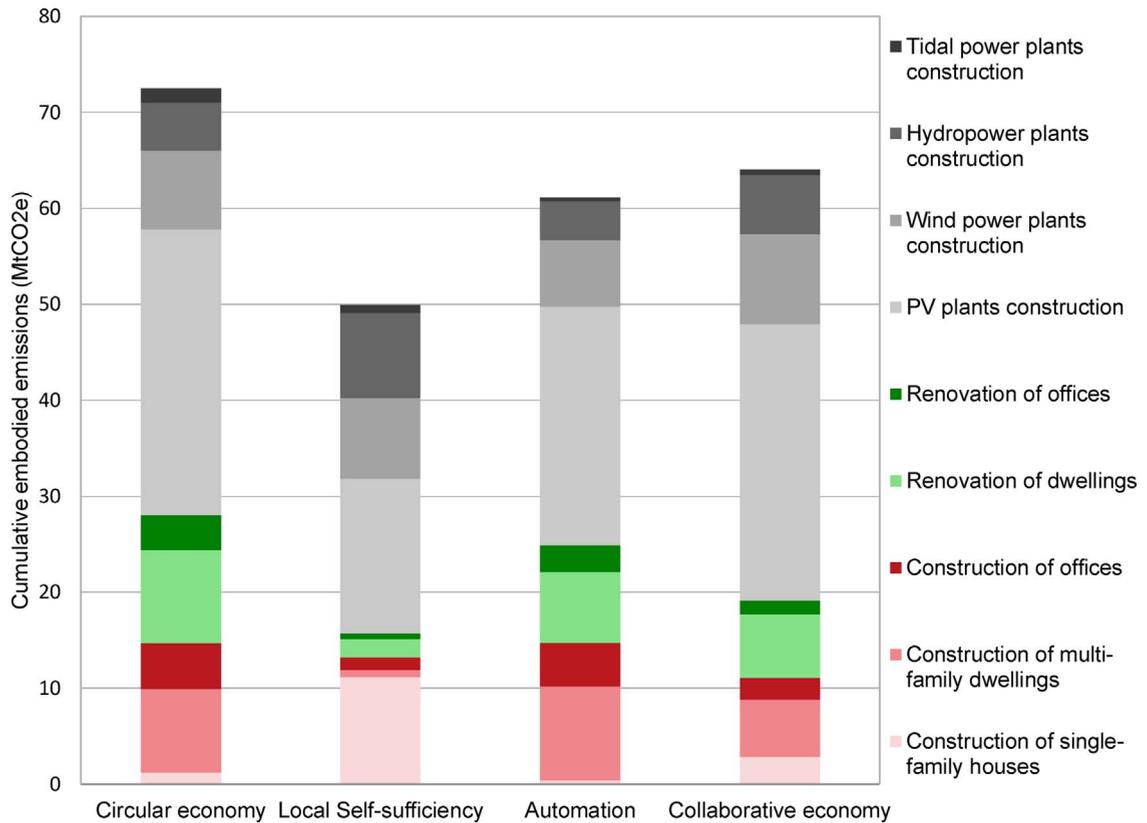


Fig. 4. Cumulative embodied GHG emissions 2020–2050 divided by contributing processes.

scenario is low due to the idea of extremely space- and energy-efficient buildings, even if the use of electricity for appliances is higher. The lowest energy demand is found in the Collaborative Economy scenario, where cohousing and office space sharing allows for both highly reduced floor areas and a reduced use of appliances through sharing.

4.2.2. Cumulative embodied GHG emissions between 2020 and 2050 associated with target fulfilment

Fig. 4 displays cumulative embodied GHG emissions from the construction and refurbishment of dwellings, offices and renewable electricity plants in each scenario between 2020 and 2050. While the calculation of emissions from electricity use in 2050 includes only the share of the country's electricity use that's attributed to the built environment, the calculation of cumulative embodied emissions includes the construction of new renewable electricity power plants to support the whole country's demand (140 TWh).

Cumulative embodied emissions between 2020 and 2050 are roughly equivalent to 60 years of emissions at the 2050 target level, or 4,3 years at the current level (within the scope of the model). This seems to indicate that embodied emissions are a significant issue to address if ambitious future environmental targets are to be met, but not a daunting problem by current standards. It should be noted that this estimation relies on assumptions about the rate of adoption of new technologies between 2020 and 2050: cumulative emissions are higher if most construction is assumed to happen shortly after 2020 than if it happens shortly before 2050 with greatly improved technology.

The most important contributing processes to cumulative, embodied emissions are the construction of new renewable electricity power plants, especially PV cells. This highlights the importance of policies encouraging the development of emerging cleaner and less energy-intensive technologies (thin film panels, quantum dot technologies, etc. (Nugent & Sovacool, 2014)). Changes in the concrete industry are also needed to mitigate emissions from the construction of houses, offices, as well as hydro-, wind- and tidal power plants. Measures such as integrated design favoring replacement and reuse of parts or streamlined recycling flows are key in the Circular Economy scenario where concrete construction remains central. Reducing the carbon intensity of renovation processes by improving technology or closing material loops is also important in the Circular Economy and Automation scenarios, that both rely on extensive renovation.

4.3. Potential conflicts and trade-offs between reduction strategies

The results presented above illustrate how low GHG emission levels for the built environment could be reached in four different scenarios. Each scenario conforms to a coherent narrative, and the combination of strategies it includes ensures its internal consistency. Nonetheless, examining strategies in a more integrative manner, outside of the framework of a scenario, can provide insights on key policies, potential trade-offs or synergies between different trajectories. Based on the presented results, reducing floor areas is the only strategy that allows a reduction in both GHG emissions in 2050, operational energy demand and cumulative embodied GHG emissions. Otherwise, strategies reducing carbon intensities (renewable energy mix, cleaner construction and renovation processes) or reducing the amount of new construction (retrofitting) do not lower operational energy demand, and strategies reducing energy demand (renovation, use of smart meters, changes in heating practices, etc.) do not lower embodied emissions. However, a more thorough assessment of these strategies would require broadening the scope of the study, as some exhibit complex synergies or rebound effects (for instance, space sharing in cohousing would reduce the amount of new construction, but it requires in turn retrofitting and reshaping existing buildings and could influence people's consumption patterns as well).

Trade-offs between strategies and conflicts between goals can arise in certain scenarios, as illustrated in the Local Self-sufficiency scenario, which exhibits both the highest operational energy demand and the lowest cumulative embodied emissions. Achieving a low operational energy demand for heating requires extensive renovation, causing an increase in embodied emissions. Since extensive energy renovation is either insignificant or counterproductive in terms of GHG emissions in 2050, is it worth carrying out ambitious renovation works if the future energy mix is assumed to be low-carbon?

Besides GHG emissions, a high energy demand imposes two other prime issues: a lower resilience towards changes in future energy supply and a possible depletion of resources. On one hand, a higher energy demand means that the issue of achieving a low-carbon energy supply becomes even more pressing. In particular, an increase in carbon intensity for heating would impact the emission level to a much greater extent in the Local Self-sufficiency scenario than in Automation. This further relates to resilience: the higher the energy demand, the more vulnerable the system is to a disruption of the supply. This is why many self-sufficiency narratives underline reducing energy demand by changing behaviors as a key strategy for resilient local communities.

On the other hand, a higher energy demand also puts more pressure on natural resources used to satisfy it. In particular, renewable electricity production requires the use of materials which are at risk of depletion, such as rare earth materials. Moreover, the extensive use of biomass for energy production and wood construction in some scenarios could increase the pressure on Swedish forests. This is a concern for both biodiversity and GHG emissions. Indeed, it was assumed that biomass for energy refers to biogenic waste and byproducts of forestry in all scenarios, as is the case currently for district heating in Sweden. Such byproducts have low emission factors (Gode et al., 2011). If instead it were assumed that trees are cut down for the sole purpose of energy production, the corresponding emission factor would increase almost thirtyfold (Swedish Environmental Protection Agency, 2017).

However, even in the Local self-sufficiency scenario where energy demand is the highest, the estimated total use of biomass for

operational energy use in buildings is actually lower compared to the present situation. It seems therefore possible that byproducts from forestry could suffice and that the energy supply wouldn't require deforestation. Wood construction between 2020 and 2050 in any scenario would require less than two years of available biomass production in Swedish forests (estimated from the current exploitation of Swedish forests, their annual increment, and the share of protected areas (Swedish Forestry Agency, 2016)). Therefore, domestic building construction doesn't seem to be a daunting issue for forest resources. However, the restricted scope of the model should be kept in mind, as sectors such as furniture or the pulp and paper industry should also be accounted for to give an estimate of the total pressure on Swedish forests. Still, it has been claimed that the share of productive forest area that is protected should be increased from 3,5% today to between 10 and 20% in order to preserve a rich biodiversity and avoid habitat fragmentation (Angelstam et al., 2010; Hanski, 2011). Moreover, increased felling can impact the balance of nutrients in forests and compete with reindeer husbandry in Northern Sweden (Egnell, Laudon, & Rosvall, 2011). A significant share of Swedish forests would have to remain unexploited in this case. At first glance, it appears that the increment of Swedish forests would be sufficient to sustain both wood construction and the use of biofuels, and still leave 20% of productive forest land unexploited. This is nevertheless a rough estimation that doesn't consider the dynamic evolution of forests or competitions with other uses of forest land, and relies on the condition that the energy demand in buildings is reduced to a large extent.

Investing in energy-efficiency will therefore still be important to build future robustness. However, as the cumulative emissions up to 2050 are directly connected to large investments, a relevant question is if there would even be the financial incentive or capacity to conduct extensive levels of renovation or new construction in scenarios exploring a societal shift in economic logic and activity. The explorations presented in this paper have partly been based on indirect assumptions about investments relating to the role of the state, regional or local government in the different scenarios, and the amount of funding available. When it comes to housing, the forms of tenure that dominate in each scenario will influence how construction and maintenance processes are financed and executed – through for example cooperative housing associations in the Collaborative Economy, or private-public partnerships in the Circular Economy. The Automation scenario also clearly relies much more heavily on technological development and efficiency measures than the other scenarios, and thus would demand more extensive investments in reshaping the built environment.

4.4. Limitations of the model and its results

The model used is suitable to compare the four scenarios within its specific scope and methodological framework. However, the scope of the model (e.g. overlooking changes in activities during free time and at work) or its limited resolution (e.g. considering all workplaces as offices) imply limited possibilities to draw more detailed conclusions on the potential of various reduction strategies. In particular, any comparison between results of the model and external indicators is invalid due to differences in scope and method. Aspects that have been identified as particularly significant would require additional investigation beyond this initial exploration. In particular, a more detailed resolution could be useful when investigating renovation/rebuilding processes (to better assess embodied emissions linked to retrofitting) and the energy mix (in particular the various forms that biofuels could take since they could exhibit a broad spectrum of emission factors). The model is based on process LCA data and doesn't consider the economic feasibility of the strategies it investigates. For these reasons, it should not be used to conclude on how easy it would be to fulfill the emission target, nor should its results be directly compared with current input-output estimates.

5. Conclusions

The aim of the explorative modelling presented in this paper was to investigate strategies for the built environment to reach a low level of GHG emissions in relation to four backcasting scenarios for Swedish society. This exploration provides a basis for discussing the societal transitions needed to ensure a just development within planetary boundaries. Ambitious environmental targets challenge how we organize, construct and use our built environment, and modelling could be seen as a method to illustrate what it would entail to reach them.

The scenarios outlined depict four particular trajectories for a society emphasizing the fulfilment of environmental and social sustainability goals, rather than focusing on continued GDP growth. Comparing these scenarios allows for an assessment of their most characteristic strategies in relation to reaching sustainability targets. Key characteristic strategies of the four scenarios investigated include: ensuring the circularity of materials and energy flows in construction (Circular Economy); radically optimizing construction and renovation processes and improving energy and space efficiency (Automation); prioritizing construction with local materials (wood, straw) and changing heating practices (Local Self-Sufficiency); and sharing space and appliances to a large extent (Collaborative Economy).

The model suggests that most strategies are efficient in so far as they impact one of these key aspects influencing GHG emissions in 2050:

- decarbonating the energy mix, by using renewable energy, waste heat, etc.
- reducing floor areas in buildings, through space optimization and space sharing

- building less (by instead retrofitting older buildings) and with cleaner processes (circular flows and less carbon-intensive construction materials)

Assuming a very low-carbon energy mix, use of electricity and heat in buildings correspond to a relatively small part of total emissions in 2050 compared to today, even though heating is still the main contributor. Under such conditions, the target could be reached with only moderate improvements in energy performance for buildings. With a decarbonated energy mix, very extensive energy-efficiency renovation reduces operational energy use but not GHG emissions, and requires higher investments and an increase in embodied emissions. A reduced energy demand nevertheless means a more resilient energy supply and a lower pressure on natural resources, which is a desirable outcome in itself. While it doesn't seem that the use of biomass for energy or wood for construction would overshoot the carrying capacity of Swedish forests in any scenario, goal conflicts could arise if it appears necessary to significantly increase the share of protected forests or avoid the fragmentation of important habitats. While GHG emissions from operational energy use are nowadays often depicted as the main environmental issue to address for buildings, the focus therefore shifts to other phases of the life cycle (such as embodied emissions from construction) or other environmental impacts (such as land use). Moreover, biofuels only have a low emission factor in so far as they come from byproducts of forestry or agriculture, or possibly algal cultures. If the energy demand couldn't be supplied with these types of fuels and would require additional deforestation, the corresponding emissions would skyrocket.

The calculation of cumulative embodied emissions between 2020 and 2050 suggests that none of the scenarios seem to entail emissions from investments high enough to make the needed transformation of the built environment a daunting environmental issue, but that embodied emissions are significant and must be dealt with (in particular for PV power plants). However, these depend on the rate of adoption of better practices, processes and technologies between 2020 and 2050. Since mitigating climate change requires that we start reducing our emissions as soon as possible, it is of importance to start envisioning less carbon-intensive processes for construction already today.

In summary, the results suggest that very different pathways can lead to a low-emission built environment in 2050, and target fulfilment will likely rely on combining strategies in different ways. The modelling exercise emphasizes that opportunities for space optimization and sharing should be investigated more in detail, since they reduce both the space to be heated and the surface of new dwellings and offices to be built. It also highlights the importance of a transition towards a low-carbon energy mix to reach ambitious targets. It displays cumulative emissions linked to necessary investments in construction, renovation and renewable electricity, and underlines the significance of emissions due to the production of PV cells. Finally, it raises the question of potential conflicts between strategies or sustainability targets. Explorative modelling can therefore be used by decision makers as a basis for discussing plans, pointing their attention towards key issues to address. There is a need to explore the role that actors within the building sector might take in order to drive various strategies, as well as challenge the current logic of investment and economic growth in society as a whole, and the built environment in particular. By formulating and investigating future scenarios both qualitatively and quantitatively, visions of a just and safe operating space for humanity can be illustrated, critically discussed, and planned for.

Funding

Financial support from the Swedish Funding Agency Formas (259-2013-1842) is gratefully acknowledged.

Appendix A

Table A1
Values for all parameters varied between scenarios.

	Circular Economy	Local Self sufficiency	Automation	Collaborative Economy	Current value	Reference
ENERGY						
Heating mix	2% non-biogenic waste incineration 73% biofuels incineration 4% solar heating 10.5% heat pumps 10.5% waste heat 41.5% hydropower 21% wind power 19% solar power 0% non-biogenic waste incineration	3.5% non-biogenic waste incineration 68.5% biofuels incineration 6.5% solar heating 14% heat pumps 7.5% waste heat 50% hydropower 17.5% wind power 15% solar power 0% non-biogenic waste incineration	11.5% non-biogenic waste incineration 68% biofuels incineration 4.5% solar heating 11.5% heat pumps 4.5% waste heat 41% hydropower 20% wind power 26.5% solar power 1.5% non-biogenic waste incineration	6% non-biogenic waste incineration 64.5% biofuels incineration 7% solar heating 14.5% heat pumps 8% waste heat 44% hydropower 22% wind power 20% solar power 0.5% non-biogenic waste incineration	60% biofuels (and biogenic waste) 25% fossil fuels (and non-biogenic waste) 7.5% heat pumps 7.5% waste heat	(Swedish Energy Agency, 2015d)
Electricity mix	12% biofuels incineration 6.5% tidal power 50% 25%	15% biofuels incineration 2.5% tidal power 0% 15%	9% biofuels incineration 2% tidal power 25% 80%	11.5% biofuels incineration 2% tidal power 35% 20%	41% hydropower 7% wind power 43% nuclear power 9% thermal power (CHP from district heating and industry)	(Swedish Energy Agency, 2015d)
Share of imported PV panels					/	/
Reduction in carbon intensity for PV due to changes in technology					/	(Nugent & Sovacool, 2014)
BUILDINGS & HEATING						
Structure of households and dwellings	4.50% SP – SH 7% 2P – SH 5% F – SH 40.50% SP – MH 28% 2P – MH 15% F – MH 0% SP – CH 0% 2P – CH 0% F – CH 45% single person 35% two-persons 20% families 16.5% single-family house 83.5% multi-family house	1% SP – SH 9% 2P – SH 64% F – SH 0.75% SP – MH 2.25% 2P – MH 4% F – MH 3.25% SP – CH 3.75% 2P – CH 12% F – CH 5% single person 15% two-persons 80% families 74% single-family house 7% multi-family house	1.50% SP – SH 2.45% 2P – SH 4.55% F – SH 24.75% SP – MH 25.55% 2P – MH 23.45% F – MH 3.75% SP – CH 7% 2P – CH 7% F – CH 30% single person 35% two-persons 35% families 8.5% single-family house 73.75% multi-family house	0% SP – SH 3% 2P – SH 19.25% F – SH 2.25% SP – MH 12% 2P – MH 16.50% F – MH 12.75% SP – CH 15% 2P – CH 19.25% F – CH 15% single person 30% two-persons 55% families 22.25% single-family house 30.75% multi-family house	17% single person 25% two-persons 58% families 42% single-family house 58% multi-family house ~0% cohousing	(Statistics Sweden, 2015)
Floor area per person	0% cohousing 53 m ² single-family houses 26 m ² multi-family houses	19% cohousing 43 m ² single-family houses 30 m ² multi-family houses	17.75% cohousing 38 m ² single-family houses 20 m ² multi-family houses 14 m ² cohousing 5% single-family houses	47% cohousing 50 m ² single-family houses 26 m ² multi-family houses 14 m ² cohousing 10% single-family houses	42 m ² in average	(Statistics Sweden, 2012)
Share of newly-built buildings in the stock and their energy demand for heating	5% single-family houses	15% single-family houses			/	(Gustavsson, Sårholm, Stigson, and Zetterberg (2011) give a renewal rate of the building stock of 0.4% to 0.6% per year.

(continued on next page)

Table A1 (continued)

	Circular Economy	Local Self sufficiency	Automation	Collaborative Economy	Current value	Reference
Share of buildings having undergone moderate renovation and their energy demand for heating	15% multi-family houses & offices	5% multi-family houses & offices	25% multi-family houses & offices	16% multi-family houses & offices		
	40 kWh/m ²	60 kWh/m ²	20 kWh/m ²	40 kWh/m ²	/	See above.
	35% single-family houses	85% single-family houses	0% single-family houses	75% single-family houses		
Share of buildings having undergone extensive renovation and their energy demand for heating	35% multi-family houses & offices	95% multi-family houses & offices	0% multi-family houses & offices	70% multi-family houses & offices		See above.
	65 kWh/m ²	100 kWh/m ²	N.A. kWh/m ²	65 kWh/m ²	/	
	60% single-family houses	0% single-family houses	95% single-family houses	15% single-family houses		
Share of avoided heating due to lower indoors temperatures	50% multi-family houses & offices	0% multi-family houses & offices	75% multi-family houses & offices	14% multi-family houses & offices		
	40 kWh/m ²	N.A. kWh/m ²	35 kWh/m ²	40 kWh/m ²	0%	
	0%	25%	0%	0%		
LIGHTING & APPLIANCES						
Baseline change in electricity for appliances (technology, behavior)	- 10%	- 40%	+ 10%	- 17,5%	/	Based on electricity use of various appliances from Hille, Simonsen, and Aall (2011)
Additional change in electricity use from smart-meters	- 5%	- 0%	- 15%	- 10%	/	(Michaels, 2008)
Change in electricity use for appliances due to sharing in cohousing	N.A.	- 20%	- 0%	- 40%	/	/
Property electricity OFFICES	10 kWh/m ² /year	5 kWh/m ² /year	15 kWh/m ² /year	10 kWh/m ² /year	10 kWh/m ² /year	Olsson (2016, personal communication)
Power per employee	0.3 kW	0.1 kW	0.6 kW	0.3 kW	0.3 kWh	Slightly higher than the consumption of one computer + monitor
Office space per employee	15 m ²	20 m ² effective 14 m ² attributed	10 m ²	14 m ² effective 7 m ² attributed	25 m ²	/
CONSTRUCTION & RENOVATION						
Share of different types of buildings in new construction	62% concrete	5% concrete	0% concrete	30% concrete	90% concrete	Arbitrary assumptions
Carbon intensity of construction processes	15% high-tech	0% high-tech	85% high-tech	22.5% high-tech	10% wood	
	12% wood	25% wood	15% wood	32,5% wood		
	11% straw bale	70% straw bale	0% straw bale	15% straw bale		
	190 kg/m ² concrete	270 kg/m ² concrete	N.A. kg/m ² concrete	230 kg/m ² concrete	350 kg/m ² concrete	Liljenström et al. (2015) for concrete.
Reduction in carbon intensity for renovation processes in 2050 compared to 2020	120 kg/m ² high-tech	N.A. high-tech	100 kg/m ² high-tech	140 kg/m ² high-tech	219 kg/m ² high-tech	Rahimi, Arhami, and Khoshnevis (2009) for high-tech/3D-printing.
	90 kg/m ² wood	110 kg/m ² wood	100 kg/m ² wood	110 kg/m ² wood	160 kg/m ² wood	Larsson et al. (2016) for wood.
	80 kg/m ² straw bale	80kg/m ² straw bale	N.A. kg/m ² straw bale	90kg/m ² straw bale	126 kg/m ² straw bale	Straw bale buildings are considered as wood buildings minus the impact from insulation materials.
	35%	10%	45%	20%	/	/

Table A2
Values for constant parameters.

Parameter	Value	Reason
ENERGY		
Carbon intensities for district heating	- 300 gCO ₂ e/kWh non-biogenic waste incineration - 12 gCO ₂ e/kWh biofuels incineration - 10 gCO ₂ e/kWh solar heating - 0,3 kWh elec. per kWh heat for heat pumps - 0 gCO ₂ e/kWh waste heat	Emission factor for plastic incineration from Eriksson and Finnveden (2009) Weighted average for current biofuels from Gode et al. (2011) Educated guess for solar heating: Moomaw et al. (2011) mention 22 gCO ₂ e/kWh for concentrated solar power for electricity, it should be lower for water heating.
Current carbon intensities for electricity	- 4 gCO ₂ e/kWh hydropower - 12 gCO ₂ e/kWh wind power - 300 gCO ₂ e/kWh non-biogenic waste incineration - 12 gCO ₂ e/kWh biofuels incineration - 8 gCO ₂ e/kWh tidal power - 16 gCO ₂ e/kWh nuclear power	Moomaw et al. (2011) Emission factor for plastic incineration from Eriksson and Finnveden (2009) Weighted average for current biofuels from Gode et al. (2011) For solar PV, a link between GHG emissions and the carbon intensity of electricity at time of production was estimated from Reich et al. (2011)
Carbon intensity of the Chinese electricity mix (for imported PV)	700 gCO ₂ e/kWh currently, 10% decrease per 5-years time period	International Energy Agency (2016) .
CHARACTERISTICS OF BUILDINGS		
Total population	11 895 000 persons	Svenfelt et al. (2015)
Current heating energy demand per m ²	130 kWh/(m ² year)	Used to calculate emissions from construction Swedish Energy Agency (2015a, 2015b, 2015c) adjusted to consider the energy demand and not the actual energy use, which differs due to the use of heat pumps
LIGHTING AND APPLIANCES		
Energy demand for lighting	5 kWh/(m ² year) dwellings 15 kWh/(m ² year) offices	Dennehy and Howley (2013) , Swedish Energy Agency (2010) and Göransson (2006) adjusted for technological improvement.
Current energy demand for the use of household appliances	1400 kWh/(person.year) single 1200 kWh/(person year) two-persons 900 kWh/(person year) family	Zimmermann (2009)
OFFICES		
Share of the population working in the tertiary sector	80%	Current data from World Bank (2014) . Kept constant to avoid a bias in the results. Without this assumption, since the work-related impact of primary and secondary sectors workers are out of scope, the emissions in scenarios where these workers represent a large share of the population (especially Local Self-sufficiency) would otherwise be artificially lower than in others.
Working time	40 h per week, 50 weeks per year	Changing working time would introduce a bias in the results (if people have more free time, emissions from their free time activities are likely to be higher, but this isn't taken into account in the model)
CONSTRUCTION & RENOVATION		
Emissions from renovation to reduce operational energy use in all dwellings by 50%	350 ktCO ₂ e/year	Brown, Olsson and Malmqvist (2014)

Table A3
Results of the sensitivity analysis (change in GHG emissions in 2050 for a 1% change compared to scenario values).

Parameter analyzed	Change in yearly per capita GHG emissions in% compared to baseline			
	Circular Economy	Local Self-sufficiency	Automation	Collaborative Economy
Decrease in building stock moderately renovated Compensated by an increase in building stock extensively renovated	+ 0,016%	+ 0,164%	0%	- 0,015%
Decrease in building stock newly-built Compensated by an increase in building stock extensively renovated	- 0,228%	- 0,119%	- 0,111%	- 0,162%
Decrease in building stock newly-built Compensated by an increase in building stock moderately renovated	- 0,234%	- 0,140%	- 0,060%	- 0,159%
Increase in Carbon intensity of electricity	+ 0,096%	+ 0,072%	+ 0,184%	+ 0,100%
Increase in Carbon intensity of heating	+ 0,316%	+ 0,686%	+ 0,390%	+ 0,484%
Increase in Floor area per person in all dwelling types	+ 0,656%	+ 0,751%	+ 0,610%	+ 0,755%
Increase in Office space	+ 0,279%	+ 0,212%	+ 0,249%	+ 0,179%
Decrease in new buildings built with conventional concrete processes compensated by equal increases for the 3 other construction processes	- 0,106%	- 0,013%	0%	- 0,051%
Increase in emission factor improvement for renovation processes in 2050	- 0,165%	- 0,008%	- 0,174%	- 0,051%
Increase in emission factor improvements for all construction processes in 2050	- 0,268%	- 0,096%	- 0,286%	- 0,127%

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.futures.2017.12.001>.

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