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Undoing the lock-in of suburban sprawl: Towards an integrated modelling of materials and emissions in buildings and vehicles

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ABSTRACT

Suburban sprawl emerged during the 20th century alongside the widespread ownership of cars. This type of low-density housing generates enduring car dependency due to the long lifetimes of buildings. A more sustainable mobility system would require a deep transformation to densify urban forms and thus foster proximity of homes, work, and services. Here we explore the evolution of long-lived residential building stocks and the potential for breaking of this lock-in by selective demolishing of detached houses to densify urban forms. We assess impacts on land use, material demand and stocks, and greenhouse gas emissions. We use a novel dynamic, Material Flow Analysis (MFA) model applied to a Swedish case study that accounts for the co-relations of building stock and car fleets through residential density. The model includes different municipality types and we explore three different speeds for the change in urban form. An accelerated densification requires more bulk materials in construction but fewer scarcer materials in cars. However, the up-front emissions of accelerated densification construction are only compensated by mobility savings in the long-term, by 2100. Emissions trends for the three scenarios are far from the urgent decarbonisation necessary. However, the denser final built environments may have social benefits and can free up significant land.

1. Introduction

Shelter and mobility represent 25% and 15% of household GHG emissions in consumption, respectively (Ivanova et al., 2016). There are significant scientific and policy efforts to reduce these emissions in the EU, including the energy efficiency of buildings directive (European Commission, 2021) and a ban on petrol vehicle sales by 2035 (The Council Of The European Union, 2022). The impacts and mitigation of these two sectors are mostly treated individually. However, buildings and vehicles are intrinsically interlinked. The home is considered a "pocket of local order" (Ellegård and Vilhelmson, 2004), where daily activities start and end. Daily mobility happens from and to home and is related to work and services in the same or nearest municipalities. Proximity to activities is constrained by urban form and requires a certain level of density. The low density and residential mono-functionality of suburban sprawl often require members of the community to own and frequently use private cars, increasing income requirements (Gössling et al., 2022) and the socioeconomic metabolic level of basic daily life (Ewing and Rong, 2008; Thomson and Newman, 2018). The expansion of suburban sprawl also: increases pressure on land use, decreases biodiversity, requires subsidies, and decreases access to services (Couch et al., 2006; Ewing, 1994; Güneralp et al., 2020). Dense and mixed-function urban areas generally increase public transport use and walking (Ewing and Cervero, 2010; Gascon et al., 2019, 2020; Jacobs, 1961; Miralles-Guasch, 2002; Newman and Kenworthy, 2006).

A very large proportion of the existing built environment was created after the introduction of the car. Suburban sprawl appeared in the post-WWII in the US, hand in hand with the diffusion of car ownership (Hayden, 1984, 2002; Levinson and Wynn, 1963; Urry, 2004). The long lifetimes of buildings and infrastructure in the built environment give these car-centric arrangements a large inertia and set conditions for their future use and resource consumption. While car fleets and ownership can change relatively quickly, the renewal of housing and other facilities cannot. For example, in developed countries like Sweden, car fleets are renewed every couple of decades (Morfeldt et al., 2021) hence the electrification of fleets is important in the mid-term. In comparison, the built environment has expanded continuously in the last century, accompanied by relatively minor demolition (Sandberg et al., 2016; Statistics Sweden, 2020, 2021). This generates few opportunities for

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deep transformation due to the large inertia of the building stock.

While extending durability is considered as a key strategy for sustainability for devices and infrastructure with large embodied impacts and material use and in mature energy-consuming technologies without significant efficiency improvements (Glöser-Chahoud et al., 2021; Hertwich et al., 2019; Skelton and Allwood, 2013; van Nes and Cramer, 2006), the building stock does not only commit emissions due to its own operation but also from the accompanying mobility system. We need a broader scope to address the connection and influence between systems. Further extending the useful lives of buildings to pay off their initial investment of embodied emissions and construction materials could potentially result in greater vehicle emissions and material use over time. Conversely, demolishing buildings and building more compact communities would mean greater emissions and material use, but lower emissions in mobility demands.

This lock-in of the built environment towards mobility is analogous to carbon lock-ins of other types of infrastructure. That is, infrastructure that is either used and which drive emissions or that become retired and are stranded assets (Fisch-Romito et al., 2021; Seto et al., 2016; Unruh, 2000). While lock-ins have been thoroughly analyzed for energy systems such as coal power plants (Cui et al., 2019; Davis et al., 2010; Hauenstein, 2023; Tong et al., 2019) and for iron and steel (Vogl et al., 2021), there has been very little attention to the quantification of urban lock-in, which may have even longer lifetimes and inertia.

Reyna and Chester (2014) explained the lock-in of energy efficiency and challenges to expanding the residential stock in Los Angeles. On smaller scales, previous research quantified induced mobility impacts (manufacturing and operation) with Life Cycle Assessments (LCA) of existent or newly built residential buildings (Anderson et al., 2015; Bastos et al., 2016; Lara Allende and Stephan, 2022; Lausselet et al., 2021; Nichols and Kockelman, 2014; Norman et al., 2006; Saner et al., 2013; Stephan et al., 2022; Treolar et al., 2000). Integrated LCA assessments of buildings and transportation show the significance of mobility in environmental impacts. For example, 62% of GHG emissions are mobility-related in a Norwegian "net-zero emissions" neighbourhood (Lausselet et al., 2021), and about half of the life-cycle emissions in the 3 types of districts in the urban region of Munich, Germany (Anderson et al., 2015). Despite this emerging LCA literature, the transformation of the built environment for new mobilities has yet to be explored, especially at-scale. Densification of buildings and neighbourhoods has been addressed in LCA but not considering the effects on mobility (Allan et al., 2022; Meier-Dotzler et al., 2021).

Material Flow Analysis (MFA) has been used to address the past and possible futures of building stocks and their effects on material use and GHG emissions (Cabrera Serrenho et al., 2019; Fishman et al., 2021; Hingorani et al., 2023; Lausselet et al., 2020; Müller, 2006; Oorschot et al., 2023; Pauliuk et al., 2021; Yang et al., 2022; Zhong et al., 2021), and separately for car fleets (Billy and Müller, 2023; Fishman et al., 2021; Morfeldt et al., 2021; Nakamoto et al., 2019; Pauliuk et al., 2012, 2021; Roca-Puigròs et al., 2023; Serrenho et al., 2017). Such MFA studies often include exogenous material efficiency strategies, and don't consider the constraints and co-relations that housing sets on mobility or vice versa. For instance, while vehicle use and ownership could decrease through cultural shifts, structural urban transformations that reduce the distance to activities by increasing density might be necessary to reach larger reductions. Lanau et al. (2019) reviewed the MFA literature on built stocks and highlighted that there has been a focus on construction materials and a lack of analysis of urban form and lock-in effects.

These research approaches have different comparative advantages that can help fill research gaps: the geography literature explains the relationships of urban form and mobility; LCA can quantify transport emissions in the assessment of existing residential buildings (but has not assessed urban transformation); MFA models explore possible futures of buildings and transport, but so far only with exogenous assumptions and not in a sectorally integrated way. In this study, we combine these approaches to endogenously consider the joint dynamics of both buildings and transport sectors using an integrated model.

We use the case study of Sweden's municipalities from 2020 to 2100, divided into 10 municipality types. This integrated dynamic MFA includes apartments, single-family houses, and cars. We calculate GHG emissions and materials in car production and use, and dwelling construction. To the best of our knowledge, this is the first attempt to assess a country-wide long-term densification strategy incorporating the interactions of buildings' and vehicles' emissions. Specifically, we analyze the dilemma faced when considering whether to demolish infrastructure to densify urban forms for enabling active mobility and public transport. We explore potential futures by considering different speeds for demolishing and building different types of new buildings along with other critical factors, with three scenarios with different speeds of demolition of single-family housing and shares of construction of single-family houses and apartment buildings.

2. Methods

2.1. Model

Our model integrates the dynamics of residential buildings (apartment buildings and houses) and cars (Fig. 1) to estimate the emissions of car production, car use (direct and indirect), dwelling construction, and

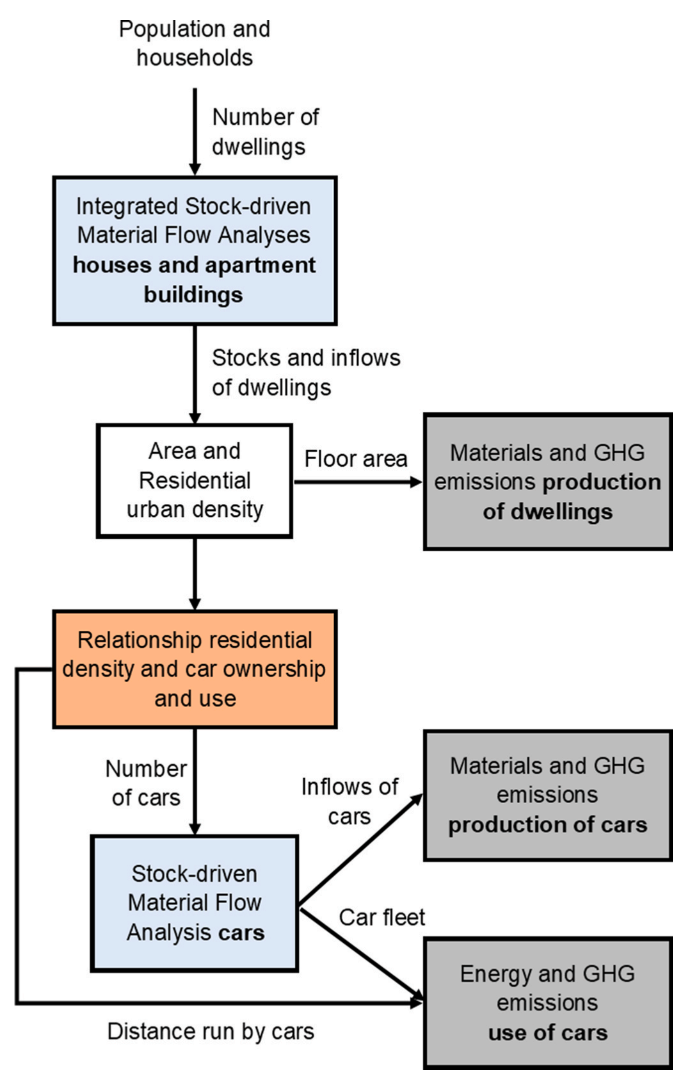

Fig. 1. Information flows between main blocks of the integrated model of residential buildings and cars. Grey boxes refer to final results and blue boxes to Material Flow Analysis. Orange box refers to the relationships in Fig. 2.

materials in dwellings and cars from 2020 to 2100. Code and data are available under an open source license (https://github.com/lapersanc/dMFAResMob). We use a very long-term, 80-year perspective despite its uncertainties so we can capture the long lifetimes of buildings. This way, we can analyze the evolution, inertia, and legacy of a mature building stock through different demolishing speeds and type of buildings in new construction. Sweden's building stock is considered mature because the country's population growth is expected to be limited.

The model is driven by population and household size, which define the number of in-use dwellings. This information forms the input for the residential building stock sub-model, which is split into two: houses and apartments, each with its own stock-driven dynamic MFA. A methodological addition to our dynamic MFA is that the speed of new construction is limited by the construction sector's capacity to avoid unfeasible and unrealistic peaks of construction (see SI section 2.3 for details).

We then calculate the floor area and residential urban density from the outputs of the building stock sub-model. Here, urban density refers to the number of inhabitants per residential land use. We propose a first attempt to model endogenously the relationship of building stocks to car use and ownership through residential density using logarithmic and polynomic relationships (Fig. 2). This follows the approach of other studies that showed the link of area per capita or density to energy use in mobility for global (Newman and Kenworthy, 1989), Swedish (Næss, 1993) and Nordic cities (Næss et al., 1996). Though density is essential for mixed uses, walkability and access to public transportation, other factors are also important, for example, road design, bicycle infrastructure and culture (Cass et al., 2005; De Witte et al., 2013; Gómez-Varo et al., 2022; Rinkinen et al., 2021). These additional design factors are out of scope here as we are focussed on high level urban transformation and car use.

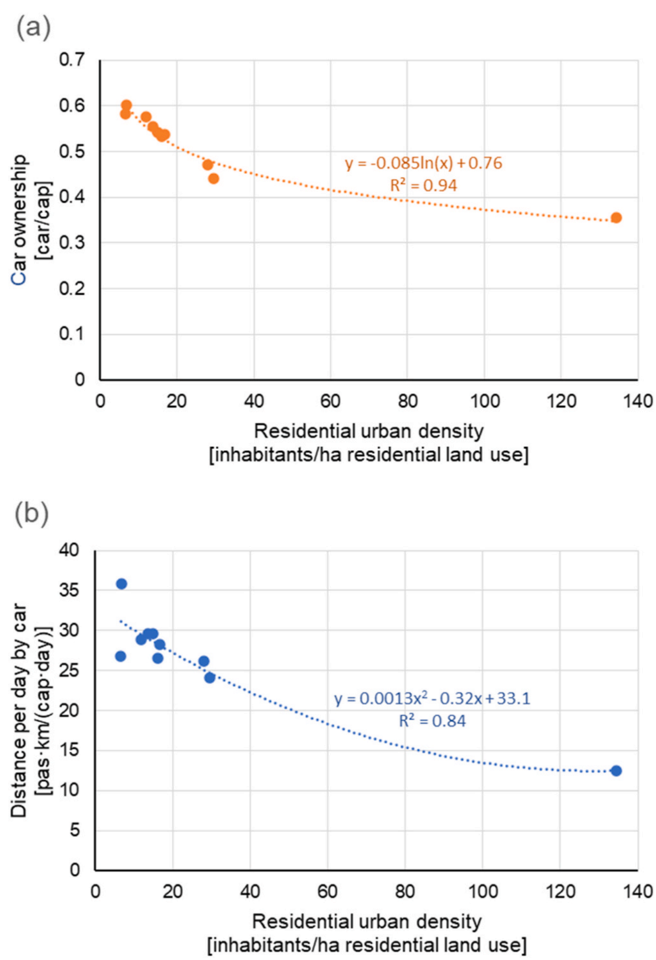

Fig. 2. Cars per capita and distance travelled by car per capita by residential urban density per municipality type (2015). Calculations are detailed in the supplementary information.

The number of cars is an input to the vehicles sub-model, which is also a stock-driven dynamic MFA. Multiplying the number of cars with the average mass of new cars per type of powertrain, we obtain the total mass of new cars. Through material intensities (kg material/kg car and kg material/m^2 dwelling), we obtain the disaggregated material requirements of buildings and cars per type. We then calculate the GHG emissions of production from emission intensities ($kgCO_{2e}$/kg car and $kgCO_{2e}$/kg material). Finally, we calculate the operational emissions of cars via fuel economies (MJ/veh·km) and emission intensities ($kgCO_{2e}$/MJ) for tailpipe and background energy system (the electricity mix and fossil fuel extraction and refining).

2.2. Case study

We focus on the case study of Sweden given the interesting characteristics of its urban environment and its relatively high data availability. While 80% of the population is considered urban, 53% of people in Sweden lived in single-family houses in 2020 (Eurostat, 2022a) and urban sprawl has been expanding in recent decades. The role of densification is also important in the Scandinavian context as Nordic countries have been working on re-densification in cities like Oslo, Copenhagen and Helsinki (Næss et al., 2011; Tiitu et al., 2021).

Sweden also has fine-scale data at the municipal level - the level at which most daily mobility functions operate. We apply the model to the 10 aggregated sets of municipalities following the Swedish classification in 2011 (Sveriges Kommuner och Regioner, 2023). This classification depends on the size of municipalities but also their economic activity and region type. Not all kinds of municipalities are included in the scenarios: Rural towns (8% of the population in 2015) are excluded because they are inherently low-density small settlements, and increasing their density would not offer improvements in mobility. Distances would remain the same as daily life activities might be carried out in other municipalities, and some economic activities, such as agriculture, are also low-density. We also exclude metropolitan municipalities (18% of the population in 2015) from the scenarios as they already have a very high share of apartment buildings.

2.3. Scenarios

2.3.1. Main densification scenarios

There are several different forms of densification. Residential urban density in inhabitants per hectare (inh/ha) depends on household size (inhabitants per dwelling), dwelling size (m^2 per dwelling) and the floor-to-land area ratio (m^2/ha). The latter two factors depend largely on the type of dwelling. Apartments are smaller than houses and have more floor area per building ground footprint.

We assess three densification scenarios based on substitution speed and ratio of single-family houses to apartment buildings: *Accelerated densification*, *Slow densification*, as well as a baseline called *Current values*. We set two exogenous variables: *type of new buildings* (k) and *lifetime of houses* (g) for each scenario (see Table 1, and a full codification

Table 1
Densification scenarios and assumptions.

Densification scenarios	Built environment	
	Type of new dwellings (k)	*Lifetime houses (g)*
Accelerated densification	100% apartments	Shorter (55 for newer houses and 120 for old houses)
Slow densification	100% apartments	Longer (120 years)
Current values	current values	Longer (120 years)

of model variables in the supplementary material). The *Accelerated densification* scenario describes shortened single-family house lifetime, making substitution faster and enabling mobility shifts but at the expense of embodied resources. The *Slow densification* scenario only employs higher density when new structures are built – building apartment buildings in place of lower-density housing when they need to be replaced. *Current values* assumes the same percentages of construction of houses and apartments as today, with relatively long lifetime of houses.

A number of premises are the same for all three main scenarios based on the Swedish context and upcoming policies and goals, which define the remaining exogenous variables. According to Eurostat estimates, Sweden's population will grow to 12 million by 2100 (Eurostat, 2022b). However, household size is stagnant. We assume a ban on new internal combustion car sales by 2030 which leads to full electrification of the fleet before 2050. Another factor is the already low-carbon intensity of the Swedish electricity mix. These settings are kept the same across scenarios, yet the effects of some of these factors are further explored as part of a sensitivity analysis described below. We also assume that construction technologies and material composition in buildings and cars are constant. This also means that a decarbonisation of the electricity mix is not reflected in the emissions in the production of buildings and cars.

2.3.2. Sensitivity analysis

To explore how different contexts could affect the outcomes of densification, we conduct a sensitivity analysis and re-run the three main densification scenarios by varying four different input parameters, yielding a total of 15 (3 × 5) scenarios (Table 2). These assumptions include: L*onger lifetime of buildings*, *More intensive use*, *EU electricity mix,* and *Non-electrified fleets*.

The sensitivity of *Longer lifetime of buildings* is tested because the durability/mortality of the buildings is one of the most uncertain variables, with little availability of benchmarks in the literature (Aksözen et al., 2017; Sandberg et al., 2016). Most of the stock built in the 20th century is still in place and built since the 1960s (Sandberg et al., 2016; Statistics Sweden, 2020, 2021). Very few buildings have reached their end of life and demolishing them is mainly related to functional and locational obsolescence (Thomsen and Van Der Flier, 2011).

More intensive use directly affects residential density and service level at low or no-investment costs. Sweden has a smaller occupation of buildings and cars than the rest of the world (Eurostat, 2022c; Fiorello and Zani, 2015). We increase gradually household size from 2.1 to 2.5 persons per household (similar to countries like Portugal and Spain (Eurostat, 2022c)), and the occupancy rate of cars from 1.3 to 1.8 persons per vehicle (see SI). These are related to the de-individualization of daily lives and to a decrease in the size of new cars, which are among the largest in Europe (ICCT, 2021).

The *EU electricity mix* has the same built environment and service level as the central scenario, and only affects GHG emissions. Electricity mix has been highlighted as one of the main parameters affecting the carbon footprint of electric vehicles (Cox et al., 2020; Mendoza Beltran et al., 2020). The Swedish electricity mix is based on nuclear, hydro and wind power, with relatively low GHG emissions intensities compared to other European nations (at 8.8 $kgCO_{2e}/kWh$ in 2020 (European Environment Agency, 2021)). As such, we also explore the outcome of densification with an average EU electricity mix in 2020 (230 $kgCO_{2e}/kWh$ (European Environment Agency, 2021)), decreasing linearly to 0 in 2050 to explore the dynamics that could be expected elsewhere.

Non-electrified fleets also has the same built environment set-up but uses the 2020 powertrain shares of new cars as the values over the whole time series. In this case, car fleets will not be fully electrified and will maintain a variety of powertrain types with larger direct tailpipe emissions.

3. Results

3.1. Stocks

The three scenarios show large differences in final stocks with very different built environments (Fig. 3). Residential density sees the largest variance of the other results, starting at 22 people per hectare in 2020 and finishing at 30 people/ha in *Current values*, 38 in *Slow densification*, and more than doubling in *Accelerated densification* (51 people/ha). The effect of the lifetimes and construction types in the scenarios is reflected in the evolution of the residential density (Fig. 4). The relatively sudden active transformation of the built environment through the shortening of lifetimes of single-family housing makes that the *Accelerated densification* increases density right at the beginning of the period. In the other two scenarios, changes are slower and mostly due to the expansion of the stock and not due to the substitution of single-family housing into multi-family dwellings due to the large inertia of existent long-lasting stocks. These densities can be translated into the share of floor area in multi-dwelling buildings. In 2020, 39% of the residential floor area are flats, which by 2100 reaches 53% in *Current values* and 76% in *Accelerated densification.*

These higher residential densities entail a shrinking in the residential land use for all scenarios, despite the increase in dwellings (from 4.8 M to 6.3 M dwellings). By 2100, *Accelerated densification* (267 kha) requires only around half of the initial 2020 land use (480 kha). For perspective, the total built land in Sweden in 2015 was 1.3 Mha, and the total arable

Table 2
Sensitivity parameters of longer lifetime of buildings, more intensive use, EU electricity mix, and electrification of the fleet, including the affected inputs to the model. Shaded cells in grey determine the common values to the main scenarios. Lifetime of single-family houses changes according to each of the three densification scenarios.

		Main scenarios	Sensitivity parameters			
			Longer lifetime of buildings	More intensive use	EU electricity mix	Non-electrified fleets
Families	*Household size (b)*	current values	current values	larger	current values	current values
Lifetime buildings	*Lifetime flats and houses (f and g)*	densification scenarios	longer	densification scenarios	densification scenarios	densification scenarios
Cars	*Occupancy rate (am)*	current values	current values	larger	current values	current values
	Size of cars (ae)	current values	current values	smaller	current values	current values
	Type of powertrain of new cars (af)	all BEV by 2030	all BEV by 2030	all BEV by 2030	all BEV by 2030	current powertrain shares
Electricity mix	*Emission intensity - fuel cycle/electricity mix (av)*	Sweden	Sweden	Sweden	EU	Sweden

			2020	2100			Difference 2100-2020		
				Current values	Slow densif.	Accel. densif.	Current values	Slow densif.	Accel. densif.
Residential density		people/ha	22	30	38	51	39%	76%	138%
Land Use		kha	480	458	361	267	-5%	-25%	-44%
Floor Area	Total	Mm^2	443	540	504	475	22%	14%	7%
	% in flats	%	39%	53%	65%	76%	35%	67%	95%
	per capita	m^2/cap	43	39	37	35	-8%	-14%	-19%
Stocks	Dwellings	million	4.8	6.3	6.3	6.3	32%	32%	32%
	% of flats	%	59%	67%	77%	85%	13%	31%	44%
	Cars per capita	car/cap	0.48	0.45	0.43	0.40	-6%	-10%	-17%
	Cars	million	5.0	6.2	5.9	5.5	24%	19%	10%
Travelled distance by car	per capita	pas·km/(cap·yr)	8821	8553	7897	6672	-3%	-10%	-24%
	per car	veh·km/(cap·yr)	14175	14654	14130	12880	3%	0%	-9%

Fig. 3. Initial (2020) and final conditions (2100) of the three scenarios. Coloured bars with the same colour are at the same scale. The colors in the two columns at the right indicate: Orange-smaller values than Current values, white-no difference, and blue-larger values.

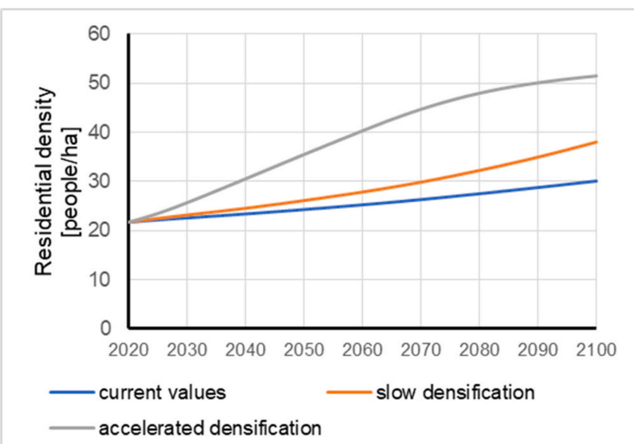

Fig. 4. Evolution of residential density in the three main scenarios (2021–2100).

land 2.4 Mha (Statistics Sweden, 2018). These changes free up 0.2 Mha of residential land use, representing a substantial saving. These reductions would be larger if we considered the land use of roads and streets. Nevertheless, the freed area is minor in the context of the whole country (41 Mha of total LU).

These different final urban forms drive significant changes in car ownership and use. By 2100, Swedish inhabitants in the *Accelerated densification* scenario would travel about 2000 pas·km/year per capita less (−25%) and own 0.7 M fewer cars (−11%) than in the *Current values* scenario. The rise in residential density is much larger than the reduction in car ownership and use. The distance travelled by car per day saturates at about 100 inhabitants/ha of residential urban density (Fig. 2).

3.2. Cumulative flows

Fig. 5 shows the total invested materials, produced items and GHG emissions accumulated between 2021 and 2100 in the three scenarios. In the *Accelerated densification* scenario, more new buildings are required, resulting in more construction materials. There are also more demolished houses. The large amounts of materials in demolition are likely not directly reusable or even fully recyclable (except for downcycling) in new buildings since architectural design does not generally consider end-of-life (e.g. most buildings are not built with reuse in mind via standardized and demountable elements) (Adams et al., 2017; Cooper and Allwood, 2012; Dunant et al., 2017).

The cumulative emissions for the three main scenarios follow similar trends and reach ca. 550 $MtCO_2e$ by 2100. No scenario meets the required reduction in emissions for net-zero goals (Fig. 6). There is very little discernible difference in cumulative GHG emissions to 2100 between the *Current values* and *Slow densification* scenarios, while the *Accelerated densification* scenario stays slightly above *current values*. By 2060 the savings in mobility start to be large enough to begin to catch up with the other two scenarios and by 2100 they are equivalent in emissions (SI: Fig. S9). This shows that *Accelerated densification* is a very long-term investment and strategy. The intensive transformation in *Accelerated densification* is not fast enough to guarantee sufficient savings in mobility to pay off the investments in construction under the conditions described by this scenario.

Emissions of car use are similar in the three scenarios due to fleet electrification, which happens parallel to building densification but is completed much earlier. There are a similar number of cars and driven distance in the first years of the three scenarios, when there are still larger GHG car use emissions due to the internal combustion powertrain types. When electrification is completed, the savings in the travelled distance do not reflect in savings in GHG emissions given the lack of tailpipe emissions and the low-carbon electricity mix. As a result, densification only saves emissions in the first few decades in terms of car use, while there are ICV cars in the fleet. This way, car production becomes the highest source of emissions of the four stages we considered in the model.

3.3. Which factors influence the results?

Different contexts impact the effects of densification, and we examine the sensitivity of the results to variants of four parameters as described in the methodology section (Fig. 7). Two parameters directly affect the number of dwellings and cars: *Longer lifetime of buildings* and *More intensive use*. The other two parameters (*Non-electrified fleets* and *EU electricity mix*) relate to the type of cars and the electricity mix, which directly affect GHG emissions.

Among these four parameters, *Non-electrified fleets* (2020 powertrain shares of new cars as the values for the whole time series) is the only one provides significant GHG savings in the *Accelerated densification* scenario compared to the *Current values* scenario (−13%). In the *Non-electrified fleets* variant, the *Accelerated densification* scenario generates lower yearly emissions than current values around 2035. In the main scenario, with the electrification of the car fleets, *Accelerated densification* only generates lower emissions from 2060 on, when yearly emissions are already low for the three scenarios (SI Figure S9). The electrification of fleets in

			Total (2021-2100)			Difference to current values	
			Current values	Slow densif.	Accel. densif.	Slow densif.	Accel. densif.
Construction	Area	million m^2	263	224	258	-15%	-2%
	Flats		163	207	242	27%	48%
	Houses		99	16	16	-84%	-84%
	Dwellings	million dwellings	3.2	3.2	3.7	-1%	15%
	Flats		2.4	3.1	3.6	27%	49%
	Houses		0.8	0.1	0.1	-84%	-84%
Demolition	Dwellings	million dwellings	1.7	1.6	2.2	-1%	31%
	Flats		0.7	0.7	0.7	0%	1%
	Houses		0.9	0.9	1.4	-3%	55%
Production	Cars	million	26.6	25.9	24.0	-2%	-10%
Distance travelled by car	by people	pas·km	8771	8494	7373	-3%	-16%
	by cars	veh·km	6747	6534	5671	-3%	-16%
Emissions	TOTAL	$MtonCO_{2e}$	561	565	562	1%	0%
	Car production		255	248	230	-2%	-10%
	Car use - direct		164	164	162	0%	-1%
	Car use - indirect		51	51	51	0%	-2%
	Dwelling prod.		109	118	138	9%	27%
Material inflows	Dwellings	Mton	186	199	232	7%	24%
	Cars	Mton	48	46	43	-2%	-10%
	lithium	kton	262	255	236	-3%	-10%

Fig. 5. Total invested resources and produced items in the three scenarios (2021–2100). Coloured bars with the same colour are at the same scale. The colors in the two columns at the right indicate: Orange-smaller values than Current values, white-no difference, and blue-larger values.

the context of a low-carbon electricity mix reduces emissions. This generalised emission reduction in all 3 main scenarios means there are insufficient emission savings via decreased travel distance that balances out the investments in densification. Overall, electrification of the fleet plays a large role in emission mitigation and makes the densification strategy less effective. While this may be expected, this happens even with an initial electricity mix with a higher carbon intensity (*EU electricity mix*). Since the car fleet is electrified simultaneously with the decarbonisation of the electricity mix, the impact of the high emission intensity in the first years is minor.

With other material efficiency strategies such as increasing lifetime of buildings or the combination of larger household sizes, smaller cars and larger occupancy rates, the number of constructed dwellings decreases sharply (by 1 million). However, while dwellings are very sensitive to *Longer lifetime* and *More intensive use*, GHG emissions are not. The emission trajectories are also similar between densification speeds. In the end, densifying more or less quickly generates a similar amount of emissions at the end of the time interval of analysis.

4. Discussion

An accelerated transformation of the built environment implies larger upfront emissions in construction, though it generates savings in car production and use in the long term. However, the scenario results are somewhat counterintuitive. Despite the very different scenarios investigated, overall emission trends are similar and do not move towards the needed net-zero goals. However, the three scenarios do have very different material and land implications. Urban densification frees up of considerable amounts of land, halving land use compared to today. The saved land could be even greater if we included the saved land for roads and streets. This freed-up area is close to where people live and could be used for recreation, carbon sequestration, local food production, and more.

The different scenario results show a trade-off between the demands for materials in buildings and in cars. An accelerated densification requires larger material inflows for buildings (compared to the current construction rates), while it curbs demand for car materials including critical materials such as lithium. The supply of both critical materials and some bulk materials, such as sand, may be an issue in the future (Calvo and Valero, 2022; Churkina et al., 2020; de Blas et al., 2020; Ortego et al., 2020; Zhong et al., 2022) and therefore, policymakers should take into account both types of materials. However, a faster change of the built environment could also be an opportunity to design with new construction methods, production processes, materials, and layouts that enable sharing, flexible housing, etc. and therefore generate further social changes for sustainability (Pérez-Sánchez et al., 2022).

The physical changes in the built environment entail changes in social practices. By 2100, travelling decreases substantially in the *Accelerated densification* scenario, by around 2000 pas·km per capita and year less than *Current values*. The decrease in car ownership is not as substantial. The relationship between car ownership and density in Fig. 2 shows how the increase in density entails a more significant decrease in car use than in ownership. Metropolitan city dwellers still own cars even though they don't use them as often. Car ownership and use could be reformulated with cultural changes that are fostered in the favorable context of denser cities (e.g., carpooling, access to public transport and services). Car travel also depends on many other economic and cultural factors that are out of scope in this study. Our results are therefore first-order assessments of the direct influence of urban form on car use. While this relationship is robust, future research could add these other factors.

The results do not provide any clear policy direction to follow. Instead, they underscore the challenge of the deep transformation of the

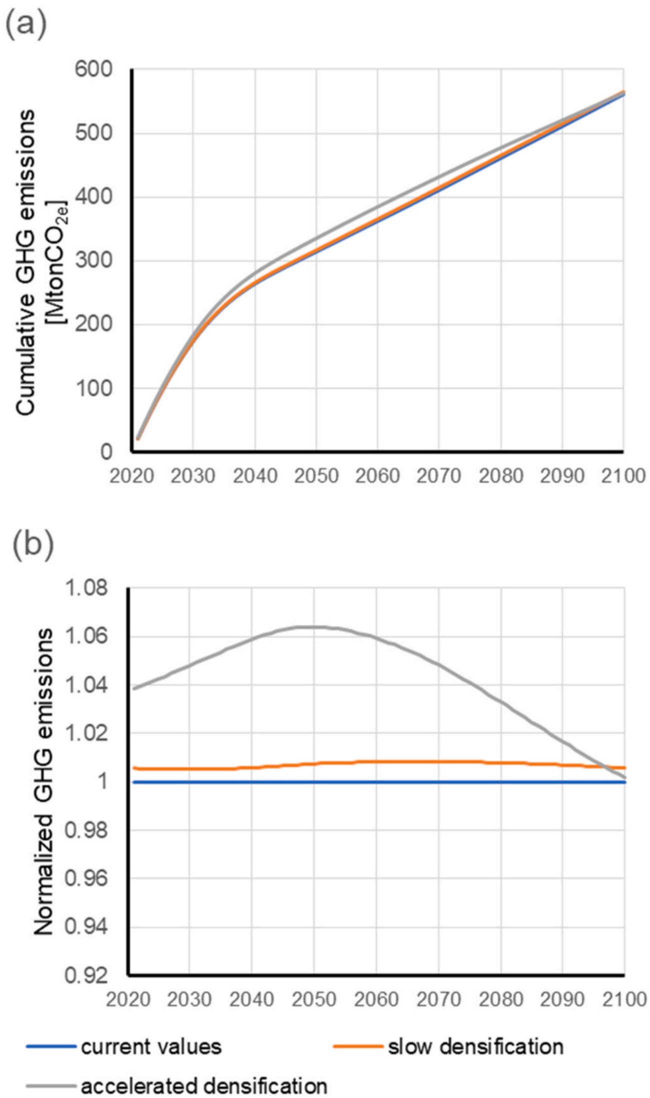

Fig. 6. (a) Cumulative and (b) normalized to "current values" GHG emissions of the three main densification scenarios (2021–2100).

built environment and the need for further research. The long lifetimes of buildings generate lock-in that affects daily life and its concomitant resource use and impacts. The densification of suburban sprawl is a long-term and gradual process. While each newly constructed multi-family building is a necessary step towards a denser built environment in the mid-term, it is a small contribution to a mature stock of buildings in the short term. This addition can change very little the average density of a municipality. Sustainable futures depend on the slow and investment-heavy transformations of the current building stock or on the possibility of changing daily life in existent built environments. For example, the paradigm of 15-min neighborhoods is not compatible with current large extensions of suburban sprawl. We must envision and plan sustainability futures to new sociometabolic regimes considering the existing enduring infrastructure that locks-in car dependency.

4.1. Modelling limitations and constraints

We propose a novel model for analysing, and providing an outlook on, the evolution of residential urban form and mobility. We present a case study as a first step and describe potential limitations. This study proposes a novel model for integrating dynamic material flow analyses of building stocks and of car fleets and their use through urban density. We produce these underlying relationships based on data from a single year, 2015 (cf. Fig. 2). Many aspects could alter this relationship: cultural changes such as a reorganization of work closer to homes, and other structural strategies such as increase of provisioning of public transport. Also, density is not the only parameter defining mobility. Therefore, while 2015 can be considered a representative year of current buildings-vehicles ratios, this relationship could be made more dynamic and cover more complexity as data become available.

The long time horizon of analysis (2100) is necessary for analysing the evolution of building stocks due to long lifetimes, but it inherently amplifies uncertainties of modelling far into the future. We did not explore possible changes in material intensity and other construction methods and design choices, to constrain the number of scenario variations. These values were taken from the most current available data for Sweden and had higher values of material intensity (kg/m$^{2)}$ for apartment buildings.

The boundaries of the system could also be extended to account for further products, sectors, and processes. For example, we did not include road stocks and public transport modes, and end-of-life in the assessment. Our analysis is limited to first-order direct effects of how investments in densification can provide substantial changes in private mobility. However, these scenarios cover the major impacts from buildings and vehicles. Also, our methods allow for further environmental benefit analysis of potential impacts other than GHG emissions.

5. Conclusions

In this study, we explored the dilemma between increasing building lifetime at the expense of maintaining suburban sprawl. This dilemma represents a lock-in of car use and land use based on urban form. Lock-in has been previously analyzed quantitatively for energy systems and power plants. However, to the best of our knowledge, this is the first study that explores this concept quantitatively for profound structural transformations of the built environment. This includes a first attempt to link urban form to car use and ownership in MFA. We explore possible futures of building stocks, their inertia and lock-in through urban density. This parameter allows us to analyze the combined effects of densification strategies on the future building stocks and car fleets, and their impacts on GHG emissions, materials, and land use. We move beyond modelling individual sectors in terms of their own resource flows and emissions to explore interdependencies and potential trade-offs of multiple sectors.

We use a Swedish case study due to the relevance of densification in the Nordic context and the availability of data at the municipal level. This kind of transformation could be further explored in countries with even lower residential density and higher car dependency, such as North America or the UK. The scope of the model could also be extended to include other factors, such as roads, public transport, and maintenance and end-of-life of buildings and cars. Further work could also explore the effects of alternative construction methods with lower impacts.

This model represents a first step for exploring deep transformations of the built environment to enable new lives and economies. Densification would also affect other daily practices and the economy, which are outside of the scope of this model, such as: create collective spaces, the shareability of devices (e.g., carsharing and carpooling: increasing car occupancy), and increase social interaction. The ultimate sustainability challenge is to generate coherent configurations of the economy and communities with a lower metabolism. This might require entirely new infrastructures and large investments to reconfigure society's fundamental structures.

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Sensitivity context	Densification scenarios	Dwellings	Cars	Materials dwellings	Materials cars	Lithium	GHG emissions
		million	million	Mton	Mton	kton	$MtonCO_{2e}$
Main scenarios	current values	3.2	26.6	186	48	262	561
	slow densification	3.2	25.9	199	46	255	565
	accelerated dens.	3.7	24.0	232	43	236	562
Longer lifetime buildings	current values	2.0	27.0	118	48	267	526
	slow densification	2.0	26.7	125	48	263	527
	accelerated dens.	2.9	24.5	183	44	240	538
More intensive use	current values	2.1	26.0	123	42	232	468
	slow densification	2.1	25.6	132	42	228	471
	accelerated dens.	2.6	23.6	165	38	209	470
EU electricity mix	current values	3.2	26.6	186	48	262	601
	slow densification	3.2	25.9	199	46	255	604
	accelerated dens.	3.7	24.0	232	43	236	599
Non-electrified fleets	current values	3.2	26.6	186	44	51	1665
	slow densification	3.2	25.9	199	43	49	1625
	accelerated dens.	3.7	24.0	232	40	46	1454

Fig. 7. Impacts of the sensitivity parameters (total 2021–2100). Coloured bars with the same colour are at the same scale. Cells with grey background indicate same values as "Main scenarios".

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CRediT authorship contribution statement

Laura À. Pérez-Sánchez: Writing – original draft, Visualization, Software, Methodology, Data curation, Conceptualization. **Tomer Fishman:** Writing – review & editing, Methodology. **Paul Behrens:** Writing – review & editing, Methodology.

Declaration of competing interest

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

Data availability

Code and input data are available in https://github.com/lapersanc/dMFAResMob.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141954.

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CONTENTS

1. Results

1.1. Time series of the main scenarios

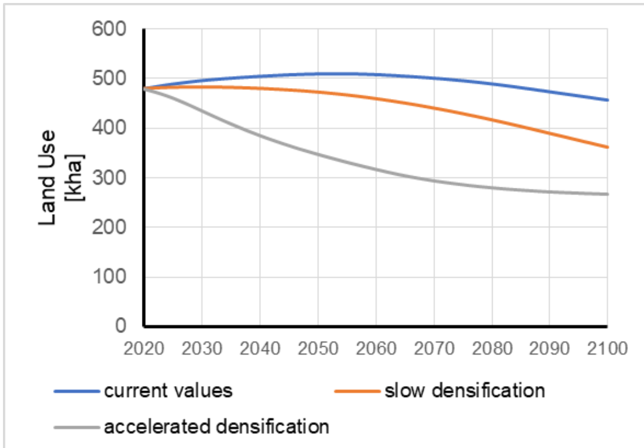
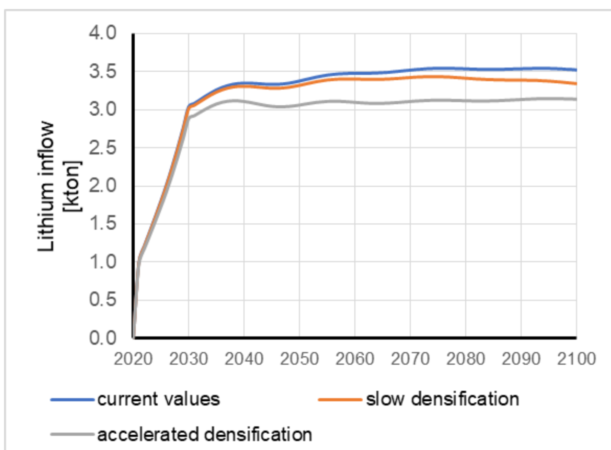


Figure S1 Evolution of Residential land use in the three main scenarios (2021-2100)



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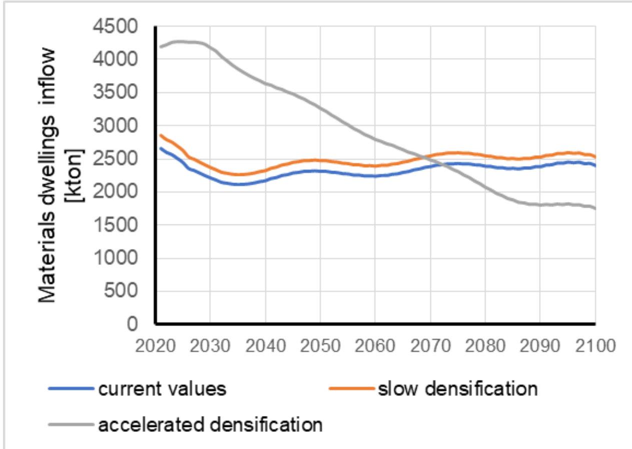

Figure S3 Evolution of materials in dwellings in the three main scenarios (2021-2100)

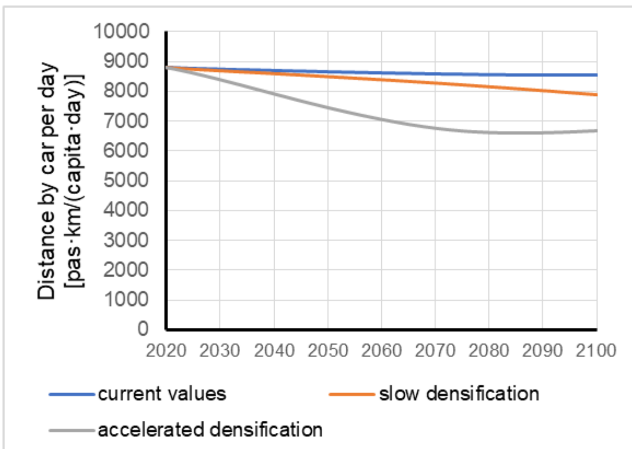

Figure S4 Evolution of distance travelled by car in the three main scenarios (2021-2100)

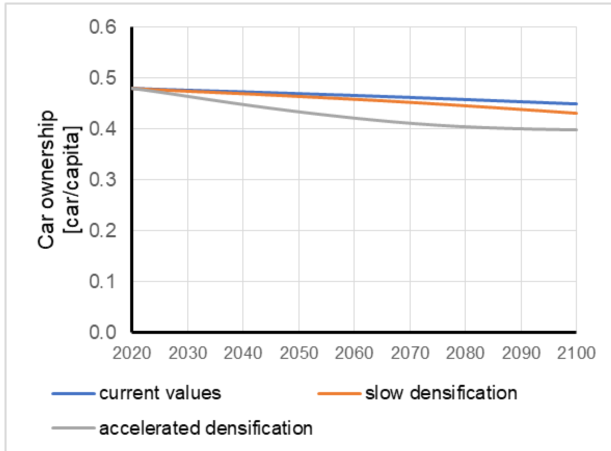

Figure S5 Evolution of car ownership in the three main scenarios (2021-2100)

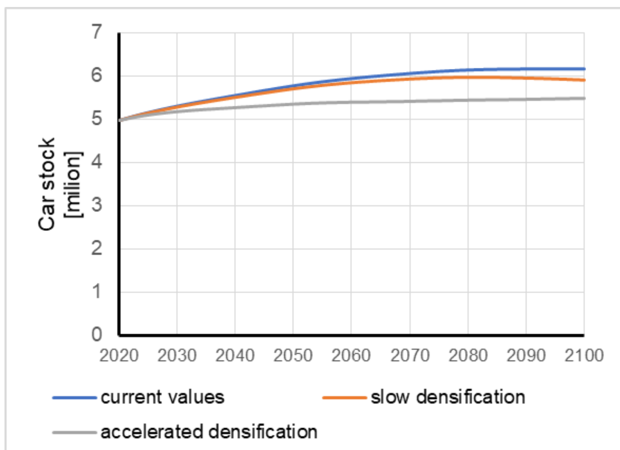

Figure S6 Evolution of car stock in the three main scenarios (2021-2100)

1.2. Sensitivity GHG emissions

1.2.1. Disaggregated per source

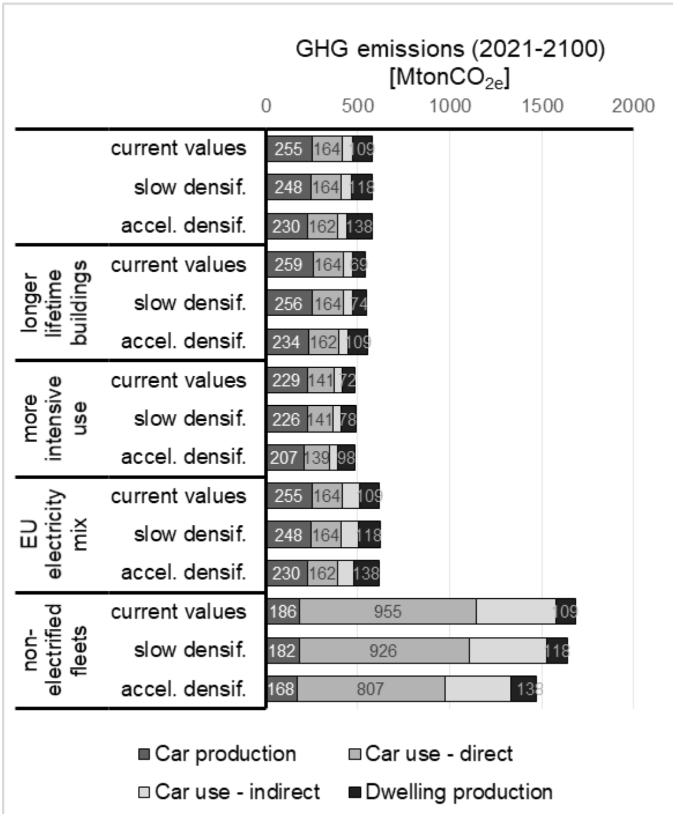

Figure S7 Total GHG emissions of the sensitivity scenarios by source (2021-2100)

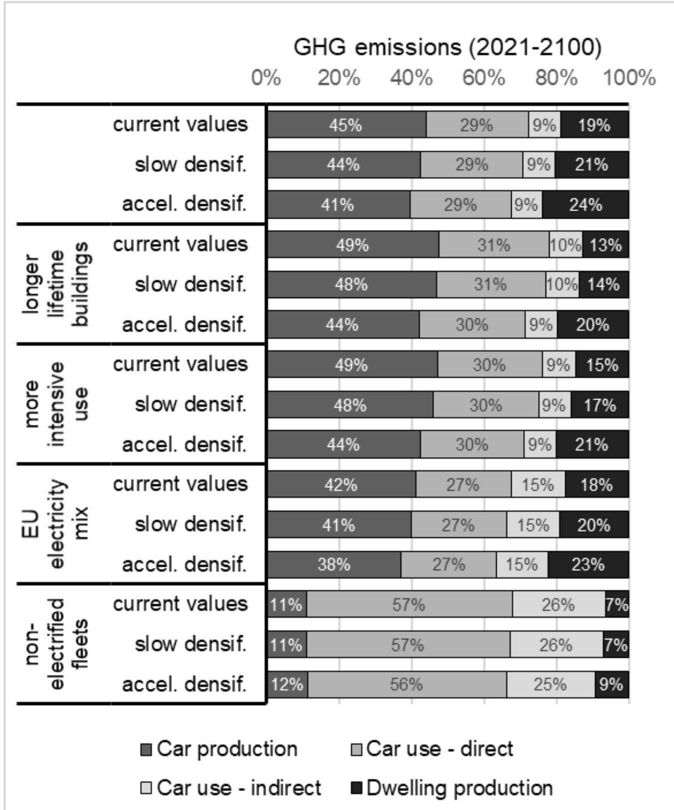

Figure S8 Share of total GHG emissions of the sensitivity scenarios by process (2021-2100)

1.2.2. Time series main scenarios and non-electrified fleets

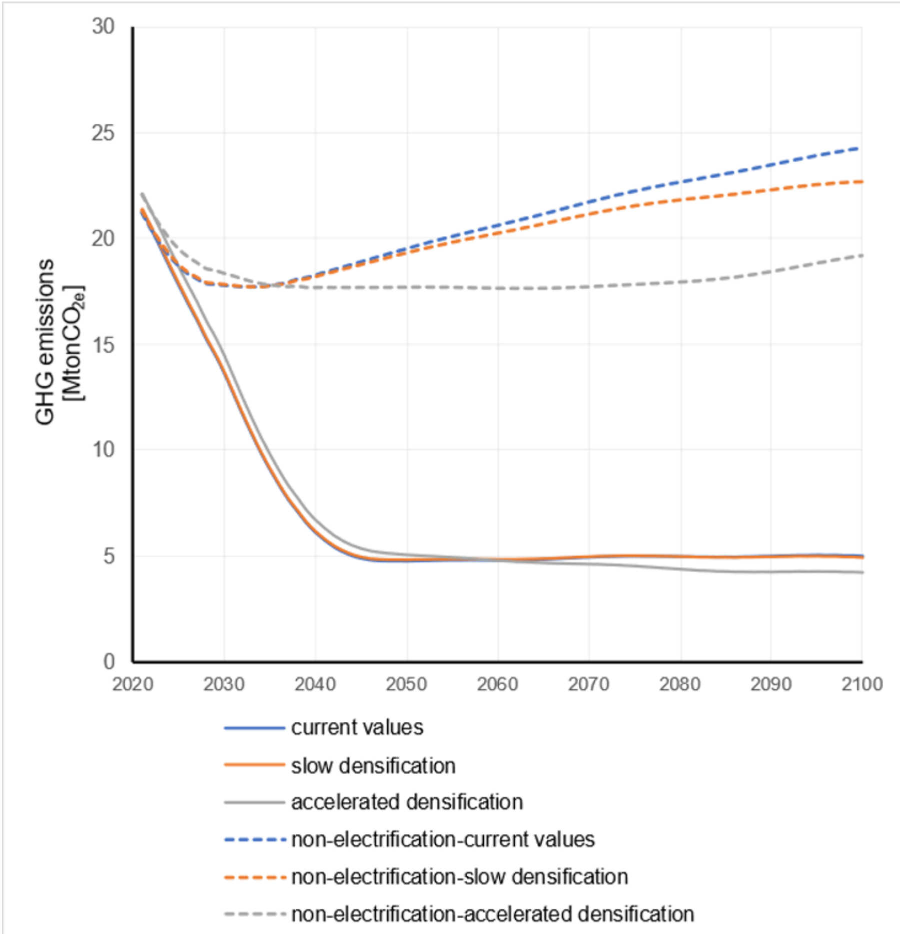

Figure S9 Comparison yearly emissions main scenarios and *Non-electrified fleets*

2. Model

The model with which we analyse the possible densification futures is an integration of stock-flow Material flow analyses of dwellings and cars linked by residential urban density (Figure S10). The following calculations are made for each year and municipality type.

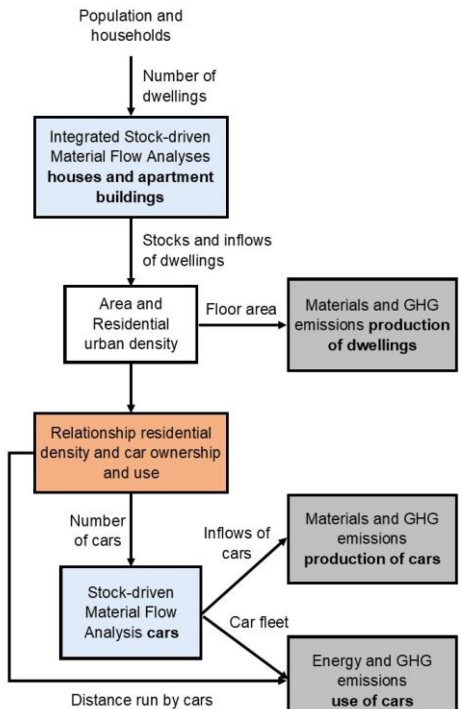

Figure S10 Overview of the information flow of the model. Grey boxes refer to final results and blue boxes to Material flow analysis.

2.1. List of indexes

- Municipality type, m (10 municipality types according to Swedish classification)
- Cohort, c (built in year t)
- Year, y
- Dwelling type, d (old/new single-family house, multi-family building)
- Material, mt (steel, wood products, lithium, etc.)
- Energy carrier, e (electricity, gasoline, diesel, etc.)
- Powertrain, p (gasoline, diesel, BEV, PHEV, etc.

2.2. Population and households

The model starts with social inputs: *(a) Population* and *(b) Household size*. The number of households is equal to population per household size for each municipality type m. The number of dwellings is equal to the number of households.

$$\text{households}_m = \text{dwellings}_m = \frac{\text{population}_m}{\text{household size}_m}$$

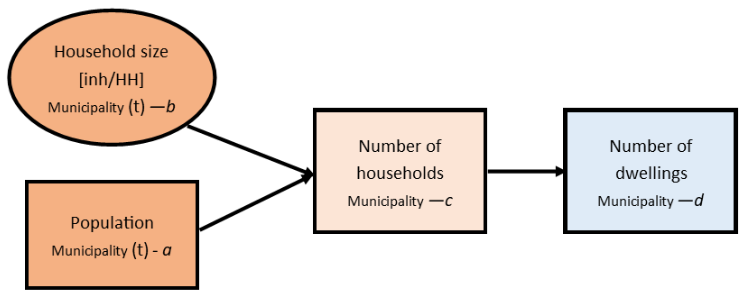

Figure S11 Subsystem of calculation of number of dwellings.
Orange refers to social data, blue to technical data. Dark refers to exogenous inputs.
Rectangular boxes indicate extensive data while ellipses indicate relative data or rates.

2.3. Stock-driven Product Flow Analyses houses and apartment buildings

The stocks, and demolition of houses and apartments are calculated through their corresponding lifetime models. The unit of analysis is the number of dwellings. The basis is the dwelling stock of the previous year (annualized demolishing rate).

$$\text{stock}(y, c) = \text{stock}(y - \mathbf{1}, c) * \mathbf{sf\_annualized}(\mathbf{y} - \mathbf{c})$$

The common way to calculate this would be with the survival curve related to the initial stock of the cohort. This way, we calculate the stock of a cohort c (built in year c) in a given year y, via the original inflow and the survival curve sf:

$$\text{stock}(y, c) = \text{inflow}(c) \cdot \text{sf}(y - c)$$

The stock of the cohort in the previous year would be:

$$\text{stock}(y - 1, c) = \text{inflow}(c) \cdot \text{sf}(y - 1 - c)$$

This is, we can isolate inflow(t) from both stock equations:

$$\text{inflow}(c) = \frac{\text{stock}(y - 1)}{\text{sf}(y - 1 - c)} = \frac{\text{stock}(y)}{\text{sf}(y - c)}$$

And relate this way the stock from a cohort in a given year to the stock in the previous year:

$$\text{stock}(y) = \text{stock}(y-1)\frac{\text{sf}(y-c)}{\text{sf}(y-1-c)}$$

This provides us with a different approach to the survival curve:

$$\text{sf}_{\text{annualized}(y-c)} = \frac{\text{sf}(y-c)}{\text{sf}(y-1-c)}$$

In this paper, the lifetime curves depend on the 3 main scenarios. This is one of the key mechanisms of the model to generate different densification speeds. To calculate the requirements for construction of new dwellings, we use the equations:

$$\text{Remaining stock (t) = Dwellings (t-1) – Demolition}_{\text{apartments}}\text{ (t) – Demolition}_{\text{houses}}\text{ (t)}$$

$$\text{Requirements of new dwellings (t) = Dwellings (t) – Remaining stock (t)}$$

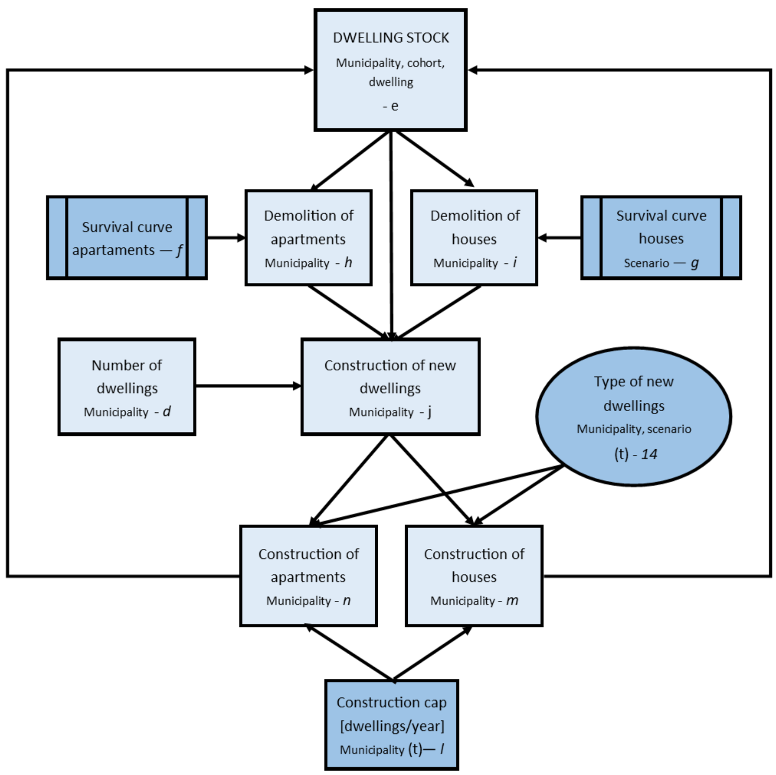

Figure S12 Subsystem of reproduction of the building stock.
Orange refers to social data, blue to technical data. Dark refers to exogenous inputs.
Rectangular boxes indicate extensive data while ellipses indicate relative data or rates.
Rectangular boxes with two vertical lines refer to functions.

The running of the PFA model will provide a first assessment of the demolishing levels and construction requirements. However, we must consider the capacity of the construction sector. Considering this construction cap, there are 4 possible results (Figure S13 and Figure S14):

- Negative required construction of dwellings: we have more buildings that we need -> construction is set to 0
- Required construction is positive
  - Required new construction is below the maximum construction capacity of the municipality type -> OK
  - Required new construction overshoots the capacity of the construction sector
    - The capacity of the construction sector could reach the stock target with fewer demolitions ($stock_{n-1}$ + max. construction ≥ $stock_n$)
    - The capacity of the construction sector cannot reach the stock target ($stock_{n-1}$ + max. construction < $stock_n$)

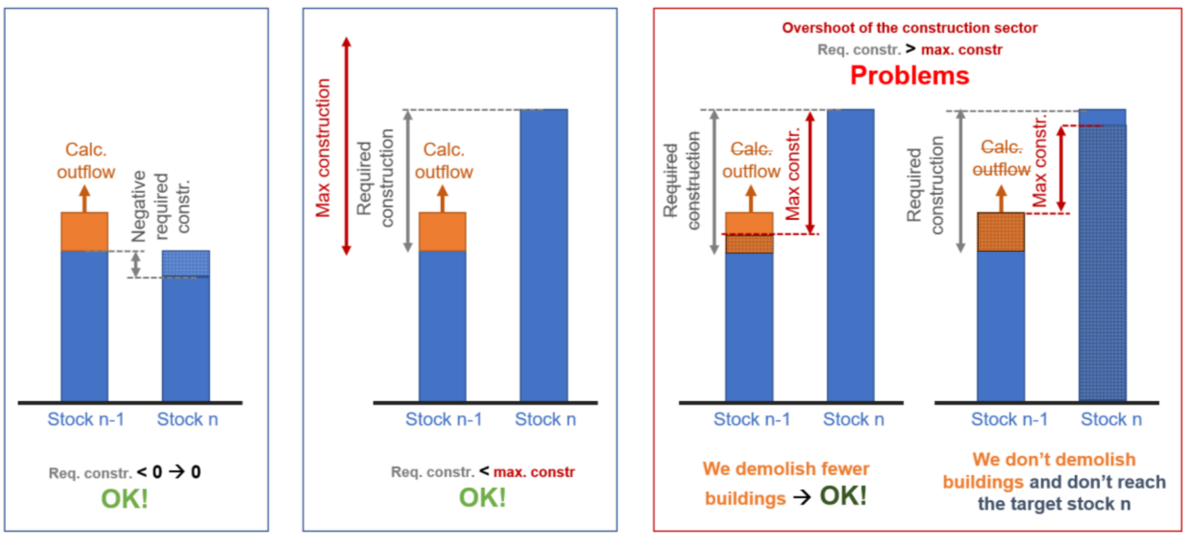

Figure S13 Possible cases in the construction requirements, maximum and outflow of the intra-year stock building dynamics

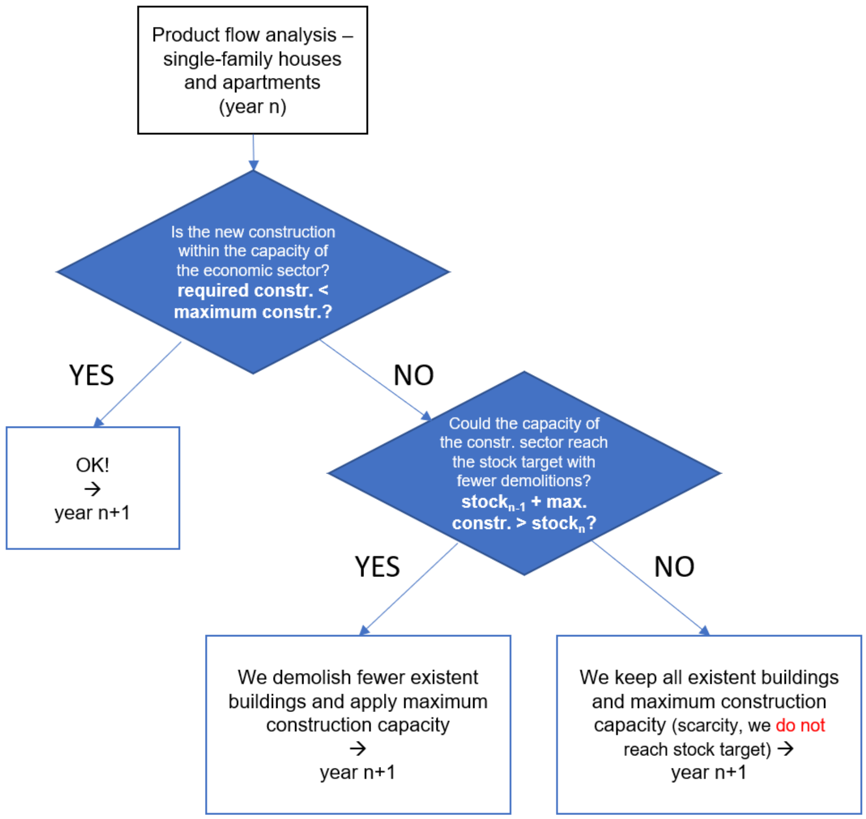

Figure S14 Flow chart of construction and demolishing requirements considering the capacity of the system

When we have the effective construction in that year, we can determine the number of apartments and single-family houses that will be built. This depends on the share of new construction (*(k) Type of new buildings* – TNB in %).

$$\text{New houses} = \text{new dwellings} \cdot \text{TNB}_{\text{houses}}$$

$$\text{New apartments} = \text{new dwellings} \cdot \text{TNB}_{\text{apartments}}$$

2.4. Area and residential urban density

From *(e) Dwelling stock* and*(o) Dwelling size* (DS) by cohort, we can calculate the total *(p) Floor* Area (FA in m^2).

$$\mathrm{FA}_{\mathrm{m,d,c}} = \mathrm{dwellings}_{\mathrm{m,d,c}} \cdot \mathrm{DS}_{\mathrm{d}}$$

$$\mathrm{FA}_{\mathrm{m}} = \sum_{\mathrm{d,c}} \mathrm{FA}_{\mathrm{m,d,c}}$$

With the *(u) Floor Space Index*, which defines the number of storeys in each type of municipality for each type of dwelling we calculate the Land use (LU).

$$\mathrm{LU_m} = \sum_{\mathrm{d,c}} \mathrm{FSI_{m,d,c}} \cdot \mathrm{FA_{m,d,c}}$$

With this *(v) residential Land Use* per municipality type and the population, we can calculate the

(w) Residential urban density of each municipality type (RUD). This is a central parameter, which integrates the dwelling and the car system. It defines both the car ownership and use (distance per capita and day) with the equations in the sections *(x) Cars per capita by urban density* (pag. 32) and *(ak) Distance per day by car by urban density* (pag. 39).

$$\mathrm{RUD_m} = \frac{\mathrm{population_m}}{\mathrm{LU_m}}$$

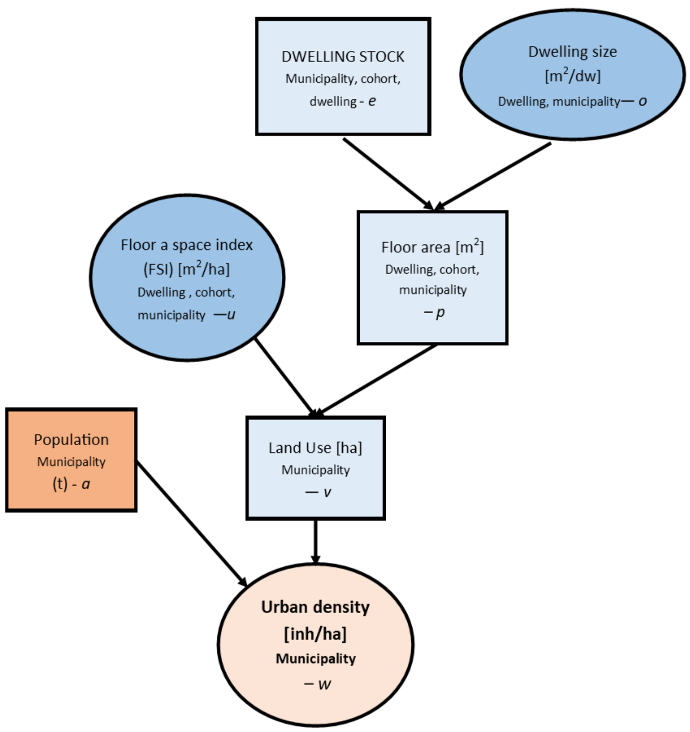

Figure S15 Subsystem of areas and density.
Orange refers to social data, blue to technical parameters. Dark refers to exogenous inputs.
Rectangular boxes indicate extensive data while ellipses indicate relative data or rates.

2.5. GHG emissions of dwelling production

With this *(p) Floor Area* of new buildings, and the *(q) Material intensity dwellings* (mat_int, in kg/m^2) of new buildings, we estimate the inflow of materials in buildings.

$$\text{mat\_dwe\_inflow}_{\text{mt,m}} = \sum_{\text{d}} \text{FA}_{\text{m,d,c}}\,(\text{c} = \text{y}) \cdot \text{mat\_int}_{\text{mt,d}}$$

Then, we approximate the GHG emissions in production of dwellings using the *(s) GHG emission intensity – materials dwellings* of material production per kg of material (GHG_int_mat).

$$\text{GHG\_dwe\_prod}_{\text{m}} = \sum_{\text{mt}} \text{mat\_dwe\_inflow}_{\text{mt,m}} \cdot \text{GHG\_int\_mat}_{\text{mt}}$$

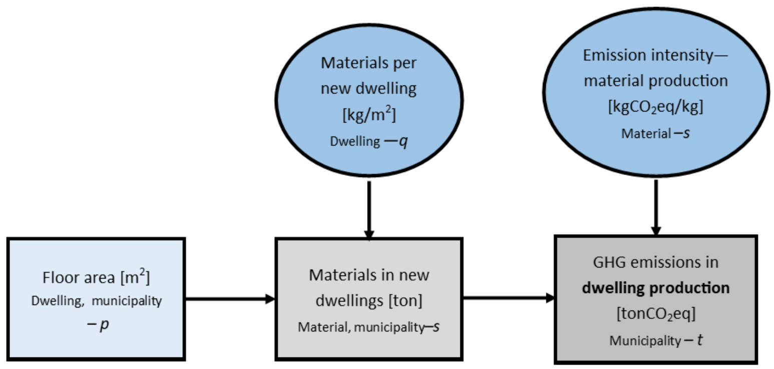

Figure S16 Subsystem of building construction emissions.
Orange refers to social data, blue to technical parameters. Dark refers to exogenous inputs.
Rectangular boxes indicate extensive data while ellipses indicate relative data or rates

2.6. Stock-driven Material Flow Analysis cars

We obtain the cars per capita each year with the function of *(x) Cars per capita by urban density* and *(v) Residential Land Use*. This is multiplied by the total population to get the number of cars in the fleet each year. Then, the cars follow a stock-driven Material Flow Analysis according to the *(ab) Survival curve cars*.

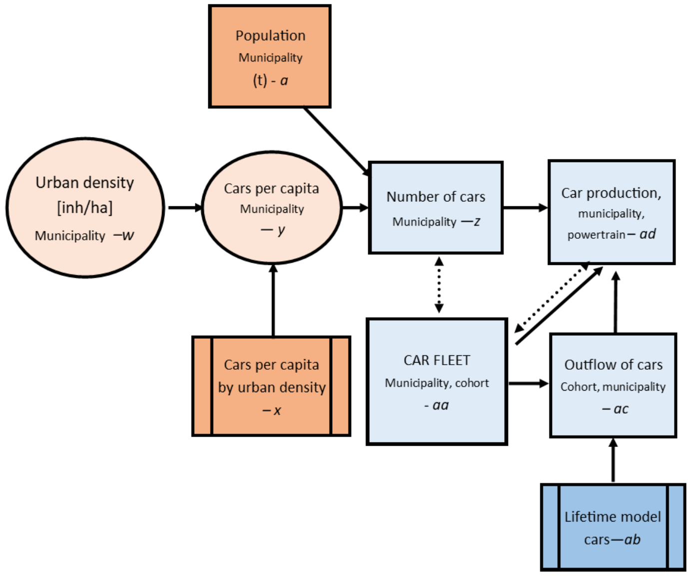

Figure S17 Subsystem of stock-driven Material Flow Analysis for car Fleet.
Orange refers to social data, blue to technical parameters. Dark refers to exogenous inputs.
Rectangular boxes indicate extensive data while ellipses indicate relative data or rates
Rectangular boxes with two vertical lines refer to functions.

2.7. Materials and GHG emissions of production of cars

The material inflow of cars is calculated using *(ae) Size of cars* (SC) and *(af) Type of powertrain* (TP) by cohort and powertrain. With *(ag) Share of lithium in car* by powertrain (lith_share), we obtain the lithium content.

$$\mathrm{mat\_car\_inflow}_{m,p} = \mathrm{SC}_{p,c}(c = y) \cdot \mathrm{TP}_c \cdot \mathrm{cars}_{m,p,c}$$

$$\mathrm{mat\_car\_inflow}_{m} = \sum_{p} \mathrm{mat\_car\_inflow}_{m,p} \cdot \mathrm{SL}_p$$

$$\mathrm{lith\_car\_inflow}_{m} = \sum_{p} \mathrm{mat\_car\_inflow}_{m,p} \cdot \mathrm{lith\_share}_p$$

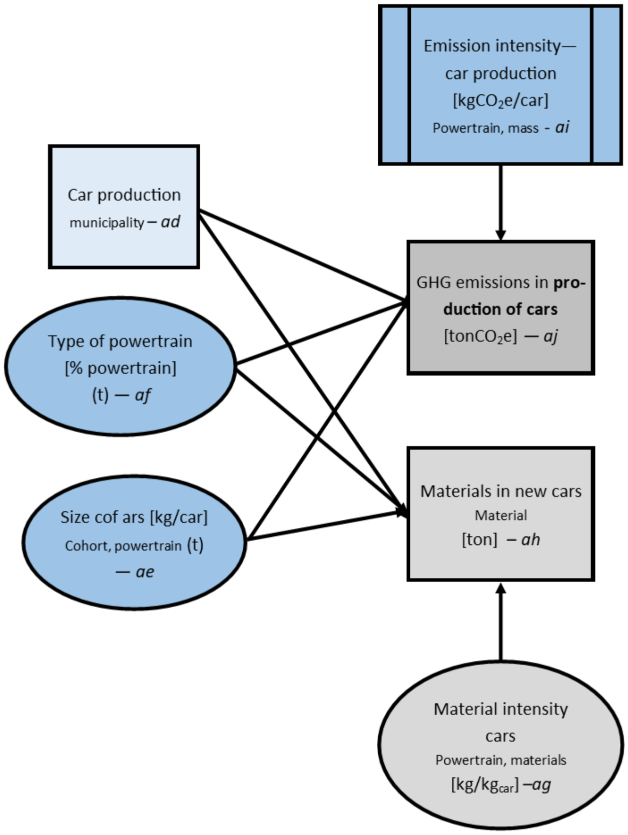

Figure S18 Subsystem of GHG emissions in production of cars.
Orange refers to social data, blue to technical parameters. Dark refers to exogenous inputs.
Rectangular boxes indicate extensive data while ellipses indicate relative data or rates
Rectangular boxes with two vertical lines refer to functions.

Each cohort of cars has diverse *(af) Type of powertrain* with a certain *(ae) Size of cars*. This information is an input for finding the *(ai) Emission intensity in car production* per car (GHG_int_car_prod), which multiplied by the total number of cars provides us with the total GHG emissions in car production.

$$\mathrm{GHG\_int\_car\_prod}_{\mathrm{car,p}} = \mathrm{f(TP, SC_p)}$$

$$\mathrm{GHG\_car\_prod} = \sum_{\mathrm{p}} \mathrm{GHG\_int\_car\_prod}_{\mathrm{car,p}} \cdot \mathrm{cars}_{\mathrm{p}}$$

2.8. Distance run by cars

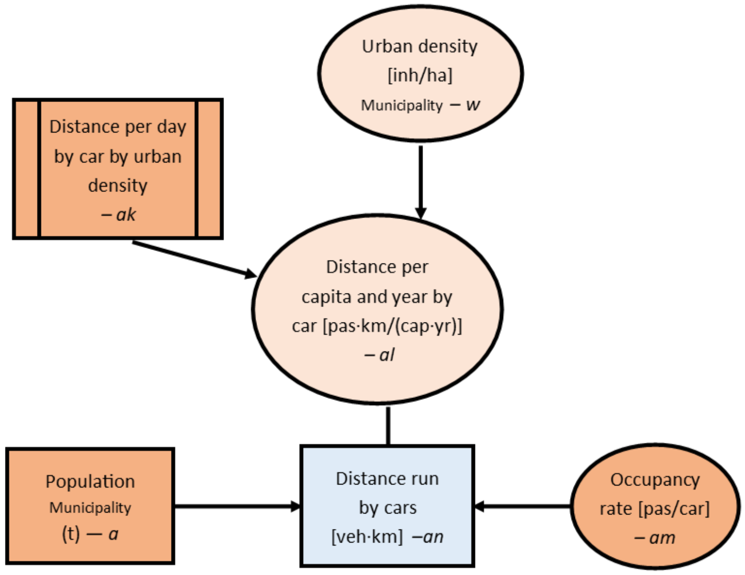

Figure S19 Subsystem of distance run by cars.
Orange refers to social data, blue to technical parameters. Dark refers to exogenous inputs.
Rectangular boxes indicate extensive data while ellipses indicate relative data or rates
Rectangular boxes with two vertical lines refer to functions.

The urban density of the type of municipality determines the travelled distance through a second-degree polynomial function (*(ak) Distance per day by car by urban density*). We multiply the pas·km/cap·yr by the total population, to have the total pas·km ($dist\_per_{tot}$). We divide it by the *(aj) Occupancy rate* (OR) to have the total distance run by cars ($dist\_veh_{tot}$).

$$dist\_per_{tot} = dist\_per_{cap} \cdot pop$$

$$dist\_veh_{tot} = \frac{dist\_per_{tot}}{OR}$$

$$dist\_veh_{veh} = \frac{dist\_veh_{tot}}{veh}$$

The distance per vehicle ($dist\_veh_{veh}$) depends on the age of the vehicle. The distance run by vehicle is then adapted to the cohorts with a coefficient. Newer cars are usually used more intensively than older cars (Figure S48). To adapt to this, we calculate the average distance per cohort (c) for the first 17 ages with a coefficient to adapt for age (*(ao) Correction distance per age of vehicle*) (Figure S49) and then we calculate the average distance run by the rest of cohorts.

From 0 to 17 years:

$$\text{dist\_veh}_{\text{veh},c\ (0-17)} = \text{dist\_veh}_{\text{veh}} \cdot \text{coef}_{c\ (0-17\ \text{years old})}$$

Older cohorts (18- years):

$$\text{dist\_veh}_{c(0-17)} = \sum_{c\ (0-17)} \frac{\text{dist}_{c\ (0-17)}}{\text{dist}_{\text{tot}}} \cdot \text{vehicles}_c \quad (\text{for } 0 \leq c \leq 17)$$

$$\text{dist\_veh}_{c(18-)} = \text{dist\_veh}_{\text{tot}} - \text{dist\_veh}_{c(0-17)}$$

$$\text{dist\_veh}_{\text{veh},c(18-)} = \frac{\text{dist\_veh}_{c(18-)}}{\text{veh}_{c(18-)}} \quad (\text{for } 17 < c)$$

2.9. GHG emissions of car use

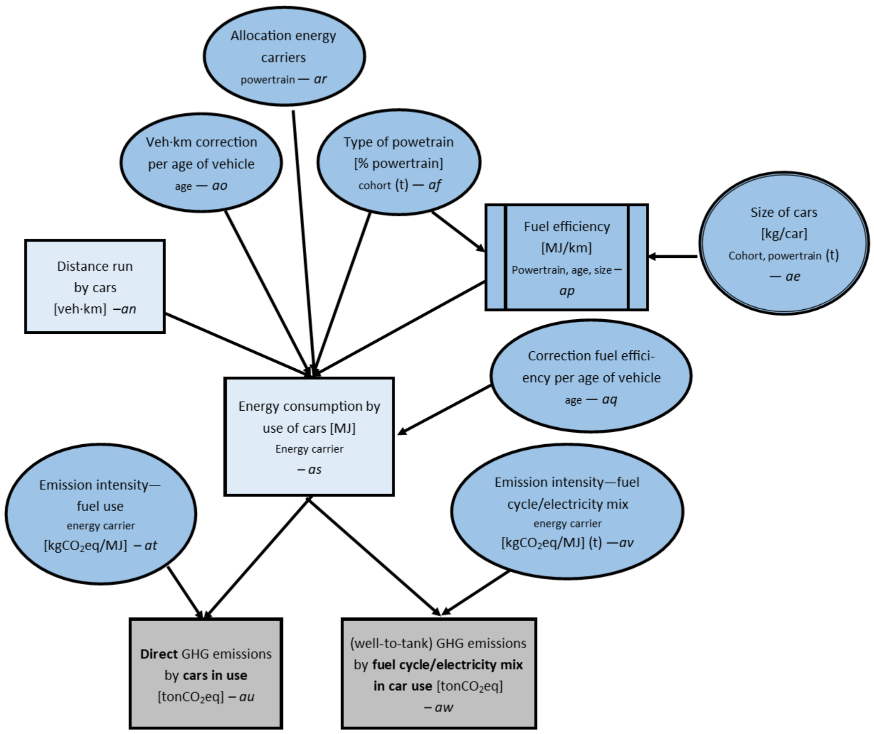

Figure S20 Subsystem of GHG emissions of car use.
Orange refers to social data, blue to technical parameters. Dark refers to exogenous inputs.
Rectangular boxes indicate extensive data while ellipses indicate relative data or rates
Rectangular boxes with two vertical lines refer to functions.

Multiplying the distance run by cars per age and the *(ap) Fuel efficiency* per powertrain p (FE), we obtain the energy consumption in use (EC_dir). We divide this by energy carrier e through *(ar) Allocation energy carriers* (coef_ec). We calculate the direct (GHG_car_use_dir) and indirect emissions (GHG_car_use_indir) in car use with these quantities of energy carriers and the *(at)*

Emission intensity – fuel use (GHG_car_use_int_dir) and *(av) Emission intensity – well-to-pump (GHG_car_use_int_indir)*.

$$\mathrm{dist\_veh}_{m,c,p} = \mathrm{TP}_{p,c} \cdot \mathrm{cars}_{m,p,c} \cdot \mathrm{dist\_veh}_{c}$$

$$\mathrm{Energy\_car\_use\_dir}_{m,p} = \sum_{c} \mathrm{dist\_veh}_{m,c,p} \cdot \mathrm{FE}_{p}$$

$$\mathrm{EC\_car\_use\_dir}_{m,e} = \sum_{p} \mathrm{Energy\_car\_use\_dir}_{m,p} \cdot \mathrm{coef\_ec}_{e}$$

$$\mathrm{GHG\_car\_use\_dir}_{m} = \sum_{e} \mathrm{EC\_car\_use\_dir}_{m,e} \cdot \mathrm{GHG\_car\_use\_int\_dir}_{e}$$

$$\mathrm{GHG\_car\_use\_indir}_{m} = \sum_{e} \mathrm{EC\_car\_use\_dir}_{m,e} \cdot \mathrm{GHG\_car\_use\_int\_indir}_{e}$$

3. Data

First of all, we initialise the system. Some exogenous inputs had to be derived from others or calculated or estimated for the different typologies. These methods are in the order of the codes of each parameter, which reflects the order in the model. However, in some cases, this is not the order for initialisation. Some data comes in extensive terms, and we calculate the intensive ratios to have benchmarks for the model. For example, we have data on *(v) Residential Land Use* that we need to calculate the *(u) Floor Space Index* that will characterise the types of buildings in the different municipalities. Through this characterisation, we will be able to calculate future Land Uses in the model.

(a) Population

Historical data comes from population by municipality type (Statistics Sweden, 2022a). Eurostat provides projections of the population trends to 2100 for Sweden and diverse sensitivity tests (Figure S21). The Swedish population in 2019 was 10,2M inhabitants. The baseline projection expects 13.6M inhabitants by 2100 (1.34 times that of 2019). The lower bound is defined by the "no migration" scenario with 8,6M, 0.85 times that of 2019. The upper bound is defined by the higher migration scenario with 15.3M and 1.5 times that of 2019.

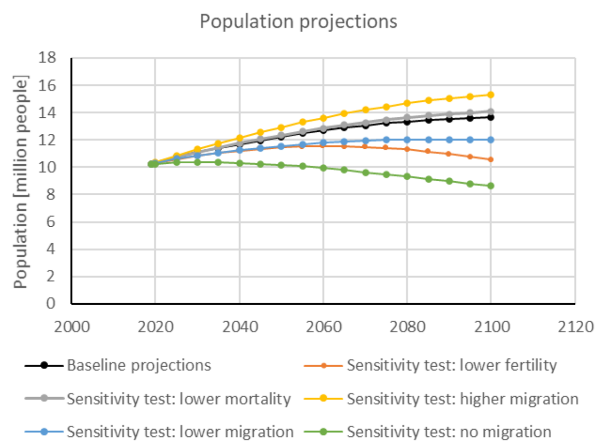

Figure S21 Population projections Sweden 2020-2100 (Eurostat, 2022b)

Then, we allocate this trend between municipalities. We assume that the shares of population by type of municipality are maintained. Therefore, the increase in population given by Eurostat for the whole of Sweden is the same in all municipality types (Figure S22).

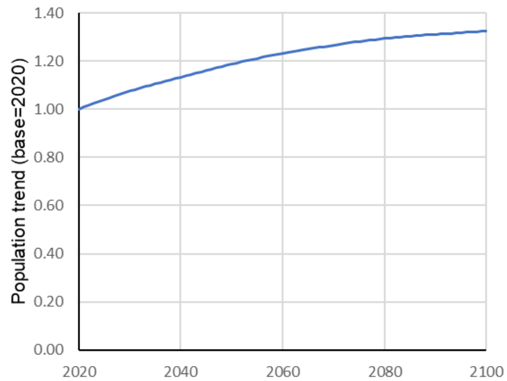

Figure S22 Population evolution for Sweden in relation to 2020 (2020-2100) **(Eurostat, 2022b)**

(b) Household size

Household size (inhabitants/dwelling) is an exogenous input in the model, but we must first calculate its initial values at the municipal level. To do this, we divide *(a) Population* by the number of dwellings (Statistics Sweden, 2020) (d) by municipality type (Figure S23).

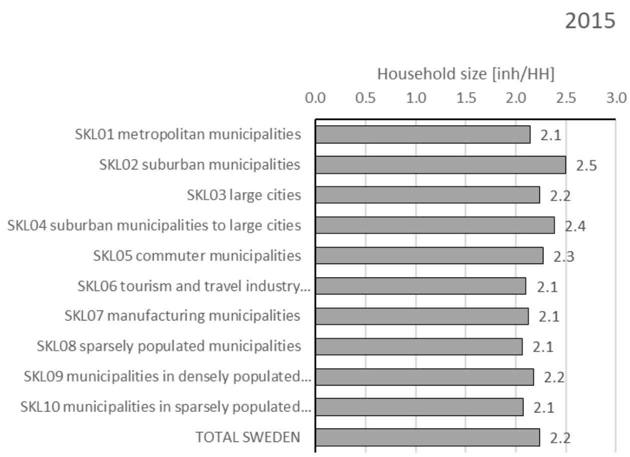

Figure S23 Household size in houses, apartments, and the average for the ten municipality types and the national average in 2015

(c) Number of households (d) number of dwellings

The main data is the number of dwellings (Statistics Sweden, 2020). We assume that the number of households equals the number of dwellings.

We have data initially for three categories of dwelling: single-family, multi-family, and other (Figure S24). First, we sum the "other" category to "multi-family." This "other" tends to be similar to multi-family; in some databases, their data is included within the same category.

Other includes student homes, elderly care homes, etc. This “other” category is small compared to the other two (Figure S24).

$$\text{Apartments} = \text{Apartments} + \text{other}$$

(e) Dwelling stock

Figure S24 also shows how the original data divides cohorts into 10-year intervals. We need to split those intervals into yearly ones.

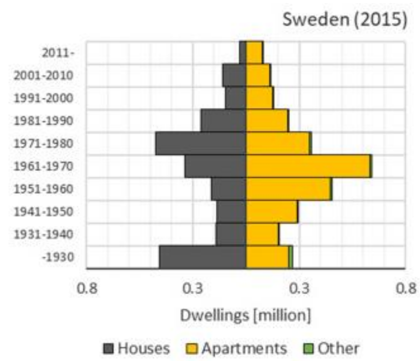

Figure S24 Demographic stock dwellings Sweden (2015) (Pérez-Sánchez et al., 2022; Statistics Sweden, 2020)

For that, we use two strategies:

- assume the construction in each year in a decade is the same (divide each existent 10-year cohort by 10).
- Divide each 10-year cohort with the shares of the production in the 10-year interval.

The initial conditions are set by the dwelling stock data in 2020 by municipality types and decadal cohort (Statistics Sweden, 2020). From 1975 to 2020, we have data on construction (Statistics Sweden, 2021b). We divide the 10-year intervals into 1-year intervals following the construction trends:

$$\text{stock}_{\text{year}} = \text{stock}_{\text{decade}} \cdot \frac{\text{construction}_{\text{year}}}{\text{construction}_{\text{decade}}}$$

For the years 1975-1980, we only take 0.6 of the construction of the decade 1971-1980. Therefore, 0.4 of the construction will be allocated to 1971-1974.

$$\text{stock}_{\text{year}} = (\text{stock}_{1971-1980} \cdot 0.6) \cdot \frac{\text{construction}_{\text{year}}}{\text{construction}_{1971-1980}}$$

For the decades in the interval 1931-1970 and the part of 1971-1980 that does not have enough data about construction (the first 4 years, a 40%), we assume that every year of the decade has the same construction.

$$\text{stock}_{\text{year}} = \text{stock}_{\text{decade}} \cdot 0.1$$

The first interval is open-ended (-1930). We keep it as it is and assume that society will aim to preserve those buildings for historical and cultural reasons. This is a very conservative assumption. Within this bulk of older buildings that are not demolished in the model, some of them will be demolished in the future. It is also likely that other post-1930 buildings are increasingly considered historical and thus maintained beyond what our survival curves state. Consequently, the assumptions balance out.

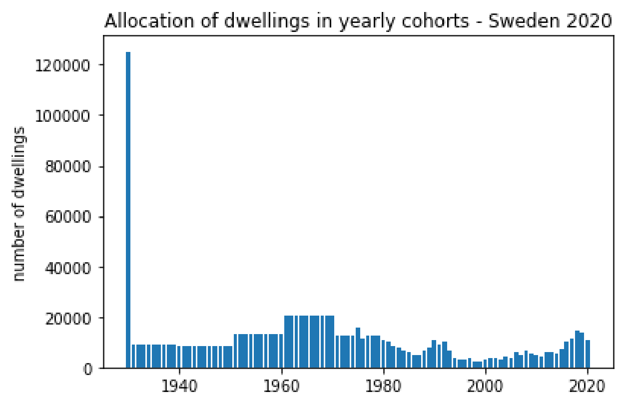

Figure S25 Final allocation of dwellings in yearly cohorts (except the first historical cohort) in 2020

(I) Construction cap

The early large-scale premature demolition of houses and substitution by multi-storey buildings can overshoot the capacity of the construction sector. To avoid having unfeasible peaks of production, we limit the yearly construction. We consider the historical construction (1975-2021) (Statistics Sweden, 2021b) (Figure S26). The historical maximum construction of dwellings was given in 1975, with 74.5k dwellings. We consider a maximum of 140k dwellings in 2030. This maximum ceiling grows linearly from 70k dwellings in 2020. We distribute this cap among municipality types with the average percentage of the construction by municipality type in the last 30 years (1991-2021) (Figure S27).

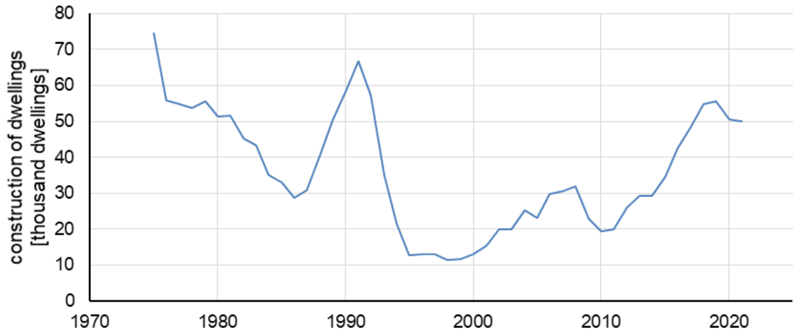

Figure S26 Historical construction of dwellings (1975-2021) (Statistics Sweden, 2021b)

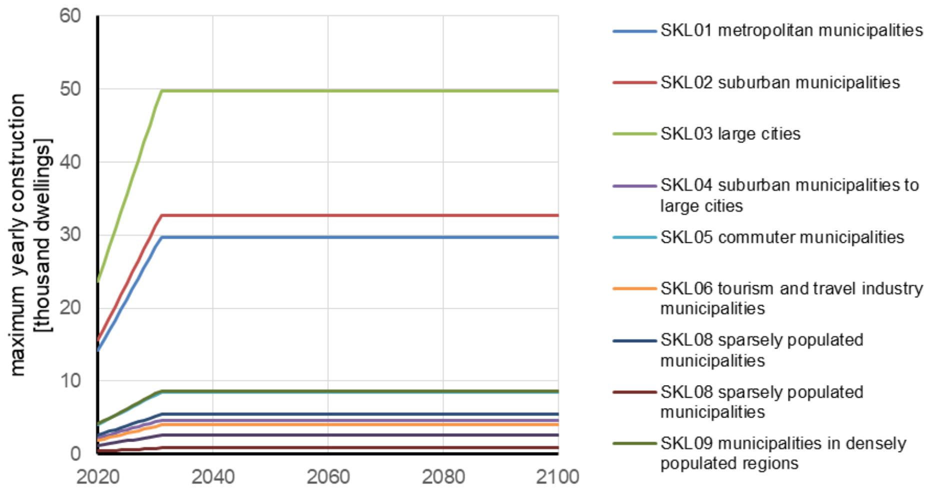

Figure S27 Construction cap by municipality type

(o) Dwelling size

The average dwelling size (m^2/dwelling) (Figure S28) is found by dividing the total Floor Area (explained in the next section) by the *(c) Number of households (d) number of dwellings*.

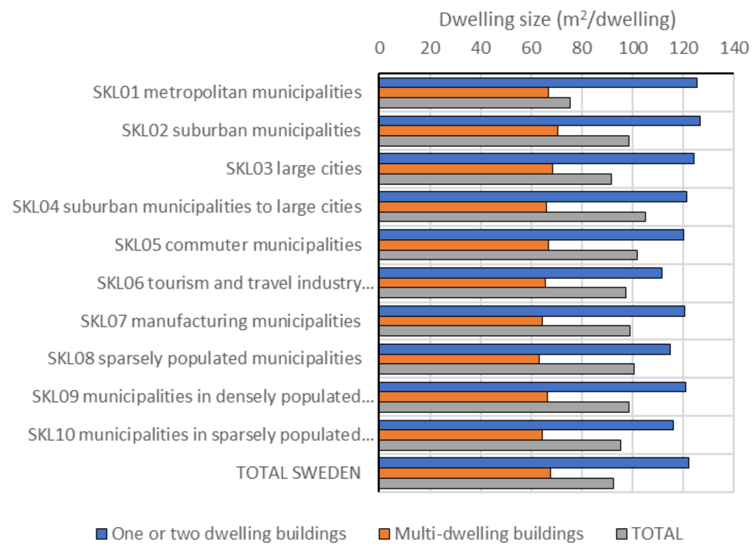

Figure S28 Calculated average dwelling type per dwelling type and municipality type in Sweden (2015)

(p) Floor Area

We define the Floor Area (m^2) occupied by one- or two-dwelling buildings and multi-dwelling buildings by municipality type we use the number of dwellings by size interval (Statistics Sweden, 2021c). For each closed $10m^2$ interval, we assign its central value (Table S1). To the open intervals in the extremes, we assume a certain area. Changes in those values do not entail large changes in the average area.

Table S1 Area intervals and assigned area value of each interval

Area interval from data	< 31	31-40	41-50	51-60	61-70	71-80	81-90	91-100	101-110	111-120	121-130	131-140	141-150	151-160	161-170	171-180	181-190	191-200	> 200
Value of the interval (m^2)	28	35	45	55	65	75	85	95	105	115	125	135	145	155	165	175	185	195	280

We have the reference of average dwelling size in Sweden of the Entranze project (2013) to check the resulting average national values:

- Multi-dwelling: 67 m^2/dwelling
- Single-family: 125 m^2/dwelling

Then, we multiply the number of dwellings by the assigned value of the interval and then sum all intervals to get the total Floor Area per municipality type and type of building.

(u) Floor Space Index

We calculated the Floor Space Index (m²/ha) in 2015 by dividing the *(p) Floor* Area per

(v) Residential Land Use (Statistics Sweden, 2018). In many of the municipality types, multi-dwelling buildings do not have many storeys (around 3) (Figure S29). Therefore, densification will not lead to crowding if it is done with the current characteristics of multi-family stocks.

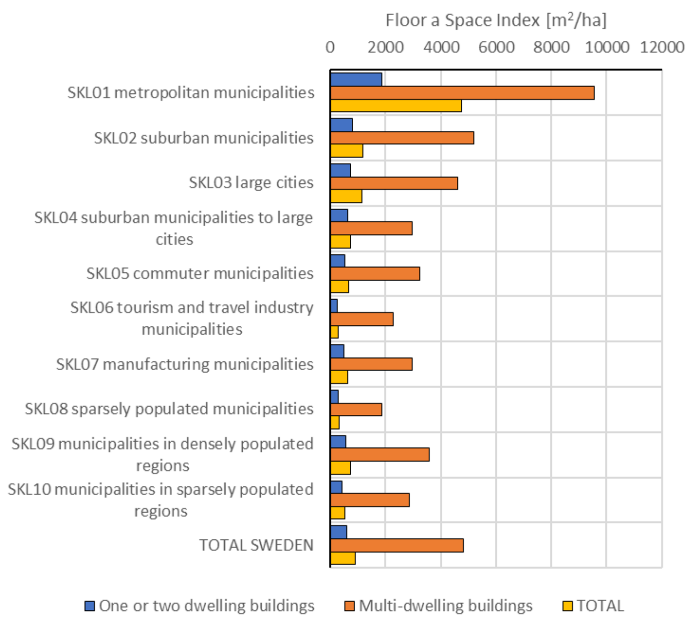

Figure S29 Floor a space index per type of dwelling and type of municipality (2015)

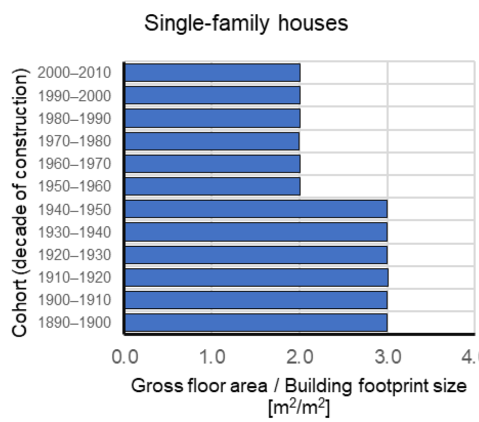

Figure S30 Ratio Gross floor area to Building footprint size by cohort (m²/m²) for Single-family houses. All are of wooden structure type. Calculated from (Gontia et al., 2018)

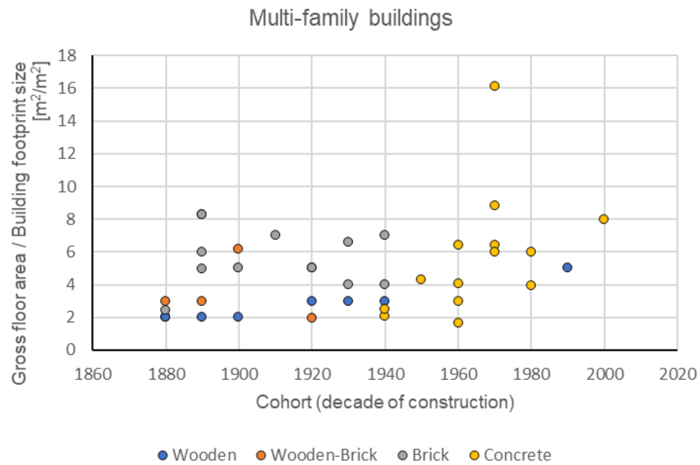

Figure S31 Ratio Gross floor area to Building footprint size by cohort (m^2/m^2) for multi-family buildings by structure type. Calculated from (Gontia et al., 2018)

However, we know that older single-family houses tend to be row houses, and it was only after 1950 that single-family houses are detached. This largely affects FSIs, being higher in the older buildings (Figure S30). Older apartment buildings are lower than new ones (Figure S31). Then, we divided the average FSI per municipality type m and building type to two categories of older and newer buildings. We set the boundary in 1950 and defined older houses as 1.2 times taller than average and older apartment buildings as 0.8 lower than average.

$$\mathrm{FSI_{old\ houses\ m}} = 1.2 \cdot \mathrm{FSI_{houses\ m}}$$

$$\mathrm{FSI_{old\ flats\ m}} = 0.8 \cdot \mathrm{FSI_{flats\ m}}$$

Then, to calculate the FSI of new buildings, we equal the land use calculated via FSI and Floor Area by older and newer buildings to the total Land Use:

$$\mathrm{LU_m} = 0.8 \cdot \mathrm{FSI_{flats\ m}} \cdot \mathrm{FA_{old\ flats\ m}} + \mathrm{FSI_{new\ flats\ m}} \cdot \mathrm{FA_{new\ flats\ m}}$$

$$\mathrm{FSI_{new\ flats\ m}} = \frac{\mathrm{LU_m} - 0.8 \cdot \mathrm{FSI_{flats\ m}} \cdot \mathrm{FA_{old\ flats\ m}}}{\mathrm{FA_{new\ flats\ m}}}$$

And equivalently for houses:

$$\mathrm{FSI_{new\ houses\ m}} = \frac{\mathrm{LU_m} - 1.2 \cdot \mathrm{FSI_{houses\ m}} \cdot \mathrm{FA_{old\ houses\ m}}}{\mathrm{FA_{new\ houses\ m}}}$$

(v) Residential Land Use

Land Use (ha) data is available only for 2010 and 2015 (Statistics Sweden, 2018). We choose 2015 as the reference year to calculate Area: Floor Area and Land Use. This Land use refers only to residential uses, which consist of the following categories: “land with one- or two-dwelling buildings” and “land with multi-dwelling buildings.”. In many cases, analyses of density refer only to cities, where the administrative border coincides quite well with the urbanised land use. However, since we worked here with all kinds of municipalities, we cannot use the total land use because they add up to the total country with large amounts of agricultural and forest land. Moreover, transport land use in rural municipalities would include long-distance highways that are not relevant for the kind of analysis performed here.

(w) Residential urban density

The residential urban density (RUD) [inh/ha] depends on household size (inhabitants per dwelling), dwelling size (m^2 per dwelling) and the floor-to-area ratio (m^2/ha). The latter two depend largely on the type of dwelling. Apartments are smaller than houses and have more floor area (FA) per land use (LU) since they are multi-storey buildings.

$$\mathrm{RUD_m} = \frac{\mathrm{pop_m}}{\mathrm{LU_m}} =$$

$$= \text{household size} \cdot \text{dwelling size} \cdot \text{floor to area ratio} =$$

$$= \frac{\mathrm{pop}}{\mathrm{dwellings}} \cdot \frac{\mathrm{dwellings}}{\mathrm{FA}\ (\mathrm{m^2})} \cdot \frac{\mathrm{FA}\ (\mathrm{m^2})}{\mathrm{LU}\ [\mathrm{ha}]}$$

Urban density is calculated by dividing the *(a) Population* by the *(v) Residential Land Use* of each municipality type. This connects the residential sector and the mobility in this model (in this case, limited to cars).

This urban density does thus not include all kinds of uses. Considering the available data, this is the best approach possible. The sum of municipalities totals the area of Sweden. Therefore, it is not easy to address how much of the land uses belongs to the core of the municipality and define its urban form. For example, transport land use includes highways connecting towns and other longer-distance infrastructure, not only streets. We know that the land uses for transport in suburban sprawl are larger than in denser urban forms, which would entail even lower densities. However, the inclusion of longer distance roads in transport land use generates noise. Other studies have different approaches to density and therefore comparability is limited. In larger cities, the non-built area might be even less significant and the whole administrative area can be chosen as the denominator for the density.

Also, some urban density approaches include other data in the numerator, such as the number of workers (Churchman, 1999; Dovey & Pafka, 2014; Ewing et al., 2010; P. Newman &

Kenworthy, 2006). Other indicators that could be useful in this sense are commercial density (retail businesses/km^2) and public facilities density (public facilities/km^2) (Gómez-Varo et al., 2022). A key factor in low-carbon mobility is proximity and multifunctionality, which requires the existence of jobs and, therefore, also potentially, services. The lack of data and the significant degree of uncertainty hinders the possibility of modelling the trends of work allocation according to the built environment. Therefore, we did not include it.

(q) Material intensity dwellings

The historical data from the material intensity of buildings in Sweden by cohort (until 2010) are gathered from Gontia et al. (2018). However, they note that the last cohorts of multi-family buildings (1990-2010) are not well represented. This is especially important because we will take this cohort as a reference for future trends and therefore there is a degree of uncertainty.

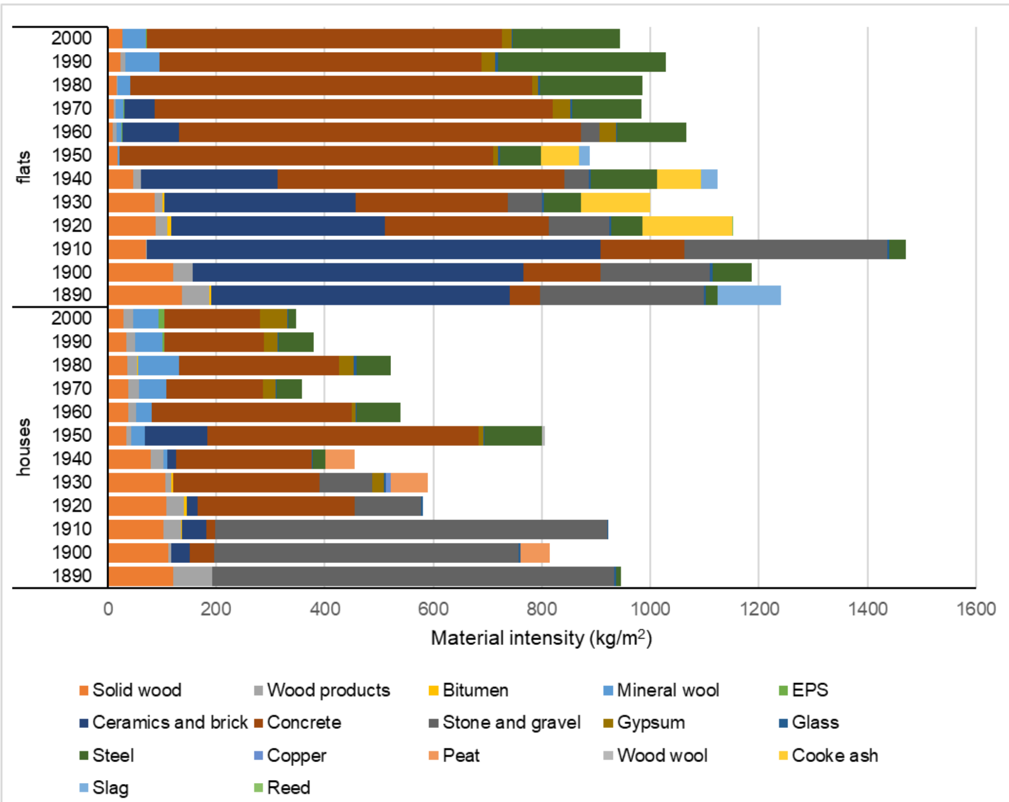

Figure S32 Material intensity of houses and apartments per material type (Gontia et al., 2018)

Gontia et al. (2018) classify the buildings by type (houses/flats), the main type of materials (wooden/wooden-brick/brick and concrete), and cohort. For single-family houses, there is only one main type of material (wooden), and all values are by decade. In this case, we do not have to work on the data. For multi-dwelling buildings, the time intervals of typologies in some cases comprise more than one decade, and there is more than one typology at the same time. For example, in Figure S31, we can see the typologies in all the decades where they are included. We do not have data on the shares of each type of multi-building in the construction in each interval. To get a single archetype by decade, we simply calculate an average of the different types of multi-family dwellings (main type of materials) that were constructed in a decade (Figure S32).

These values are constant in time for the future cohorts. Therefore, we are not considering strategies that involve any changes in materials such as lightweighting, or a more intense use of timber. In this case, houses require way less materials per m^2 than apartments. Constant material intensities are a reasonable assumption since in the last 5 or 6 decades the amount and shares of material intensity are similar for each type of dwelling. The main differences are the existence of large shares of stone and gravel before 1940 and the significant use of ceramics and brick in apartment buildings before 1950. These materials were substituted by concrete, which represents the bulk of material intensity nowadays in both houses and flats.

(s) GHG emission intensity – materials dwellings

We calculate the GHG emissions through the material emission intensity (see section *2.5. GHG emissions of dwelling production*). This data for emission intensity comes from the most aggregated categories in Lausselet et al. (2020) (Figure S33). These will be constant in time, and therefore, we are not considering possible technical improvements in the industry towards lower-emissions production (e.g., hydrogen steelmaking). The matching of categories with those of *(q) Material intensity dwellings* in Gontia et al. (2018) is shown in Table S2:

Table S2 Matching of material categories for data for material intensity and GHG emissions intensity

Materials Lausselet et al. 2020	Materials Gontia et al. 2018	GHG emission intensity ($kgCO_{2e}$/kg materials)
Concrete	Concrete	0,14
Ceramic tile	Ceramics and brick	0,60
Flat glass	Glass	1,13
Gypsum	Gypsum	0,19
Rock wool	Mineral wool	1,42
PS extruded	EPS	3,82
crushed gravel	Stone and gravel	0,00208
asphalt	Bitumen	0,07
Steel, low-alloyed	Steel	2,00
medium density fibreboard	Wood products	0,18
sawnwood - softwood	Solid wood	0,16

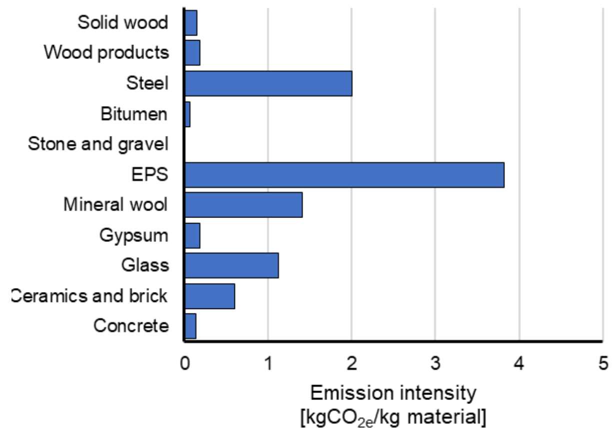

Figure S33 Emission intensity of material production for construction [$kgCO_{2e}$/kg material]

(x) Cars per capita by urban density

Following the idea exposed by Newman and Kenworthy (1989) that relates energy use in transport in cities with urban density, we use *(w) Residential urban density* to estimate car ownership.

Car ownership is tightly linked to the dwelling type and the emergent urban form of the sum of dwelling types. People tend to own more cars if they live in single-family houses. The larger land uses required by houses increase the distances to services and generate car dependency. However, car ownership does not decrease endlessly and saturates at some level of density. For example, car ownership in metropolitan municipality type in Sweden (which includes the three main cities: Stockholm, Malmö, and Göteborg). Dense urban forms have the potential of further decreasing car ownership with sharing (e.g., carsharing and carpooling) and public transport, which could increase with cultural changes. Therefore, car ownership at high densities could even decrease without any cost.

We divide the number of cars per municipality type (Statistics Sweden, 2022b) by *(a) Population* to calculate car ownership per municipality type. The logarithmic regression (Figure S34) is defined through linking *(w) Residential urban density* and car ownership for each municipality type.

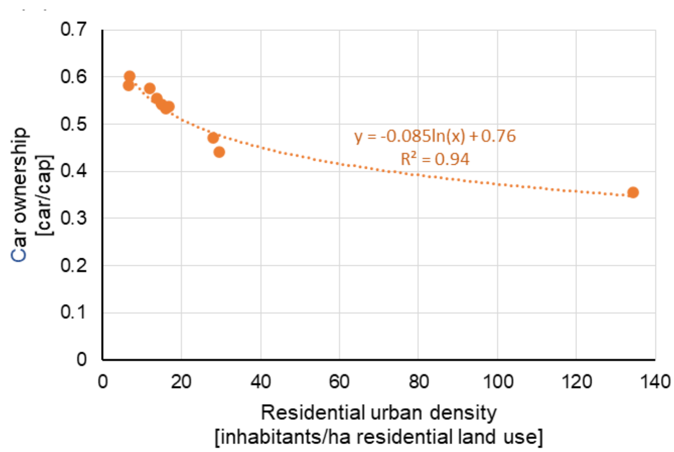

Figure S34 Cars per capita by residential urban density per municipality type and the average of Sweden (2015)

(z) Car fleet

We need the distribution of cars by cohort and municipality. We assume every municipality type follows the demographic distribution at the Swedish level. We also define the powertrain distribution per cohort for all municipality types as the Swedish average. We initialize the car fleet with the number of cars by municipality type from 2020 (Statistics Sweden, 2022b).

Cohorts are defined yearly except for the initial cohort, which includes all cars manufactured before 1985 (Figure S35). This kind of car is not usually used as frequently as newer ones and we consider these differences in distance run in the model. Other reasons explain their existence in the fleets: e.g., for occasional use or as collectible or memorabilia items. In conclusion, for calculating the distribution in cohorts for the initial stock (in the year 2020), we have the following equation:

$$\mathrm{cars}_{c,m} = \mathrm{cars}_{m} \frac{\mathrm{cars}_{c,\ \mathrm{Sweden}}}{\mathrm{cars}_{\mathrm{Sweden}}}$$

Being c the cohort, and m the type of municipality.

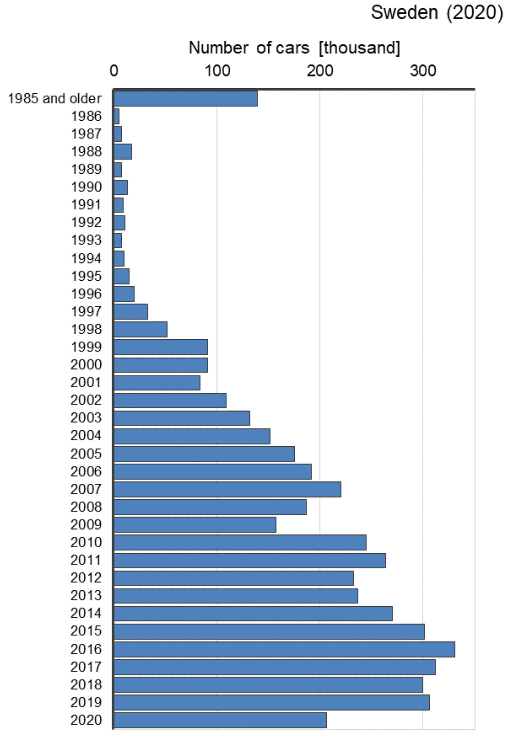

Figure S35 Demographic distribution of passenger cars in Sweden (2020) (Sweden, 2020)

(ab) Survival curve cars

We use the survival curve defined by Morfeldt et al. (2021) in their model for the Swedish car stock. The expected lifetime is 16.93 years, whereas the standard deviation for normal distribution is based on k = 0.26. They calibrated the curve from real-world data on Swedish scrappage.

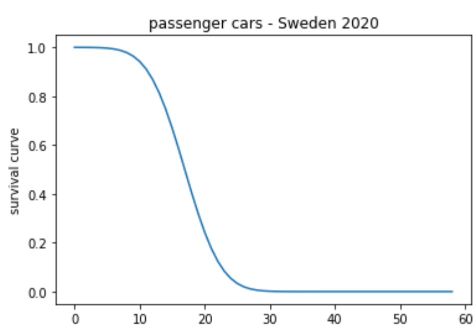

Figure S36 Survival curve of passenger cars in Sweden. Data from Morfeldt et al. (2021)

(ae) Size of cars

Car weight depends on the powertrain type and category (mini, compact, SUV, etc.). Weight (kg/car) affects, on the one hand, the specific inputs of materials (tons of materials) and, on the other hand, *(ap) Fuel efficiency*. The data of average mass in running order of new cars in Sweden from ICCT (2021) for 2001 to 2020 is not disaggregated by powertrain. Until 2015, less than 5% of newly registered cars had some degree of electrification (see *(af) Type of powertrain*). Given this homogeneity, we consider that until 2015 there were no weight differences between powertrains. All powertrain types have the average mass in running order of the whole cohort in ICCT (2021). For the years after 2015, we use archetypes of powertrain and category in Wolfram et al. (2020) as a reference to estimate the weight of new cars in Sweden. For example, we know that PHEVs tend to be SUVs and thus larger than gasoline cars. Moreover, PHEVs are heavier than gasoline cars for the same category. PHEVs are lighter than battery electric vehicles for the same segment. However, we define BEVs as being lighter on average due to the segment difference: BEVs tend to be more compact than PHEVs.

We check the match of the average weight of new cars in Sweden by cohort with the calculated with the estimated values by powertrain. We multiply the average weight of each powertrain type and the shares of new cars for each cohort. These estimations match from 99.6% to 100.5% of the value given by ICCT. The estimated average weights per cohort and powertrain from 2001 to 2020 are shown in Figure S37.

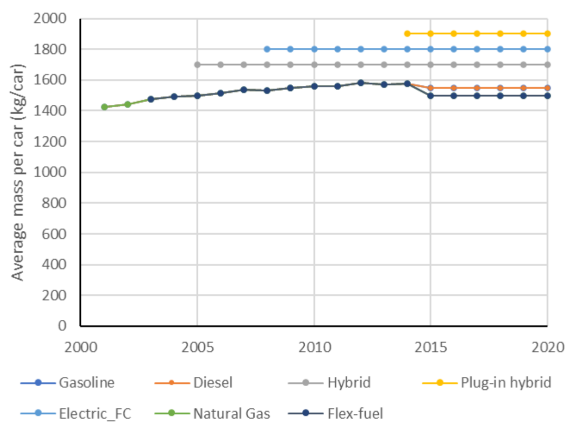

Figure S37 Estimations of the average weight of each powertrain (2001-2020)

For the older cohorts, we estimate values from the trends of weight of the different versions of Volkswagen Golf MK in Danilecki et al. (2017). We calculate the weight changes of the three older models relative to the model in 2000: the Golf MK4 (interval 1997-2003). We assume that this trend will be the same as the weight of diesel and gasoline cars in Sweden (Figure S38). We also have the reference in some points in time of the weight of new cars in Sweden from Sprei et al. (2008), which coincides nicely with our assumption. The complete initialization of the car weight considering all types of powertrain and ages is shown in Figure S39.

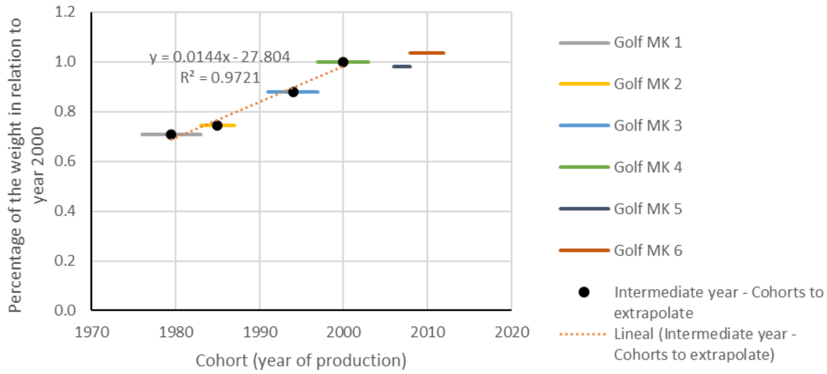

Figure S38 Weight of Golf MK models by their average year of production against the percentage of weight in relation to Golf MK4 (years 1997-2003)

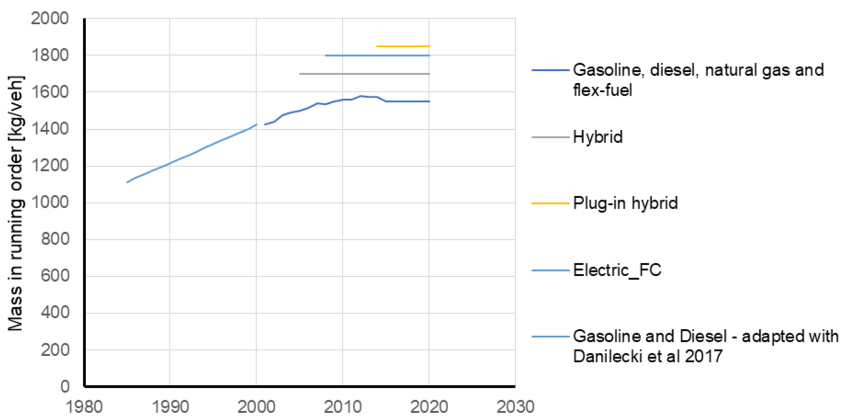

Figure S39 Initialization of mass per vehicle per powertrain type

(af) Type of powertrain

We have data for new registrations by type of powertrain from ICCT (2021) for the time interval 2001-2020. This data source does not include the older cohorts still in the fleet in 2020 (10% of the fleet). We know that the vehicle stock from 1970 to 1992 consisted basically of gasoline cars with only an approx. 3.5% of diesel cars (Schipper, 1995). We will consider this constant 3.5% the percentage of new vehicles that are diesel as well in the pre-2000 cars (Figure S41). We do not consider other types of powertrains before 2001, even though there was already a small share of new cars powered by natural gas in 2001 (Figure S40).

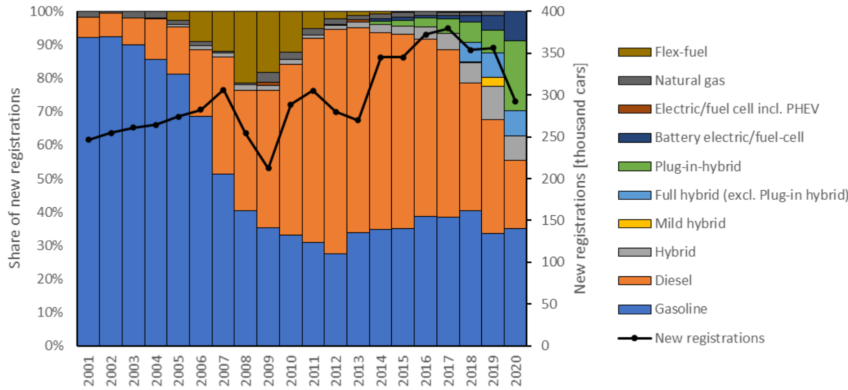

Figure S40 New registrations and share of the powertrain of new registrations in Sweden (2001-2020) (ICCT, 2021)

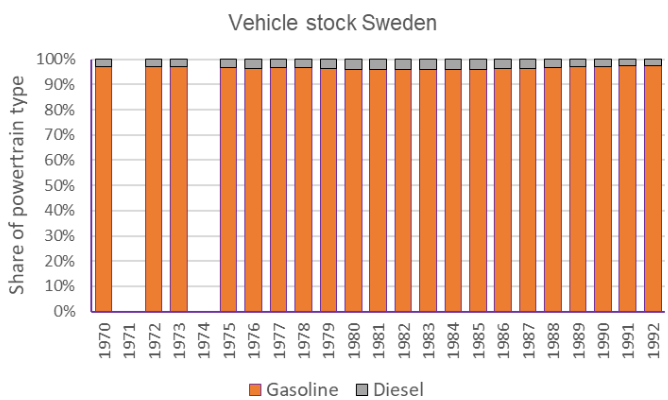

Figure S41 Vehicle stock in Sweden by type of powertrain (all ICV: Gasoline and diesel) (1970-1992) (Schipper, 1995)

The final distribution of powertrains by cohort is shown in Figure S42. We will consider that the cohorts maintain this distribution in all municipality types and in time. We know, however, that electric cars are more prevalent in metropolitan areas (Westin et al., 2018) and that diesel cars use to have a more intense (more veh·km/(year·car)) and shorter life.

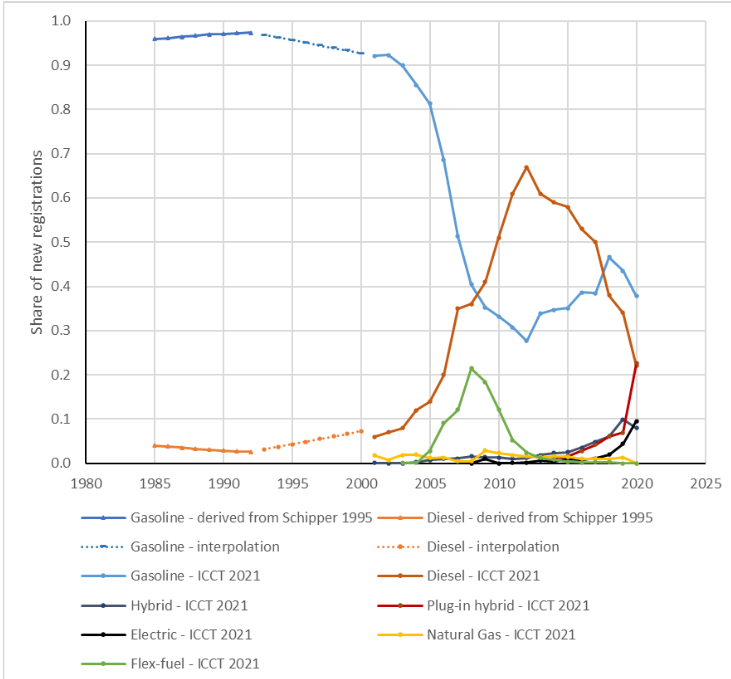

Figure S42 Final distribution of powertrain types by cohort using the different datasets and assumptions (1985-2020)

(ag) Share of lithium in cars

We assume that the share of materials is the same for every size and different for every powertrain. The percentage of lithium per total mass of cars was taken from Ortego et al. (2020). We assume that hybrids have the same share of lithium than plug-in hybrids. The data from ICEV petrol and diesel comes from SEAT Leon segment C.

(ai) Emission intensity in car production

We calculate the emission intensity in the production of vehicles with regressions for the different archetypes by powertrain and weight derived from data in Wolfram et al. (2020) (Figure S43). As in other emission and material intensities (*(q) Material intensity dwellings* in page 30 and *(s) GHG emission intensity – materials dwellings* in page 31), we are not considering possible technical improvements or decarbonization of the electricity mix for lowering the emissions of production.

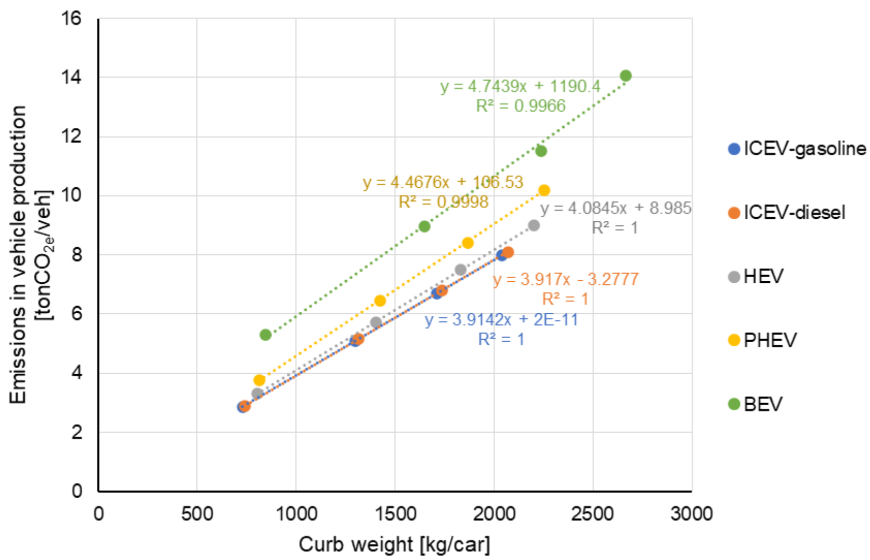

Figure S43 Emissions in vehicle production [kgCO_{2e}/veh] per curb weight and powertrain type. Data from Wolfram et al. (2020)

(ak) Distance per day by car by urban density

Urban density is a prerequisite for the proximity of services and work, including access to public transport. This main parameter broadly explains car and energy use in transport in cities. This relationship has been exposed at the level of global cities by Newman and Kenworthy (2021; 1989), but there are other studies that have unravelled this relationship quantitatively (Levinson & Wynn, 1960; Næss, 1993, 2012). Even though density is a major explanatory parameter of private motorized vehicles use and ownership, there are many other causes explaining modal choice, walking and use of public transport in cities (Cervero & Kockelman, 1997; Gascon et al., 2019, 2020). In these multivariate studies, we can see that other characteristics of the built environment as street length density and connectivity are relevant. Therefore, when applying densification strategies, the shape of the new dense urban form must be considered, and it should include other uses such as office and retail space. However, further improvements for decreasing the travelled distance could be made by changing culture or social arrangements like the prioritisation of hiring workers in the proximity of the workplace.

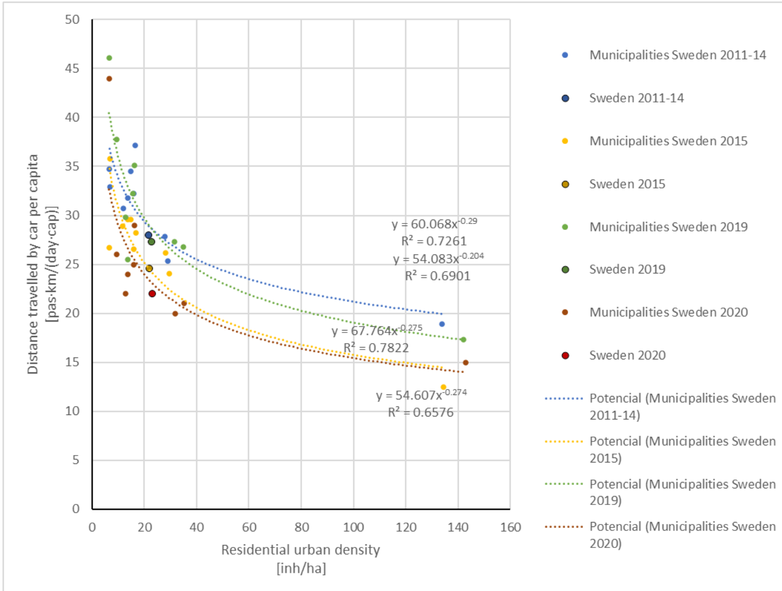

Figure S44 Distance traveled by car per capita by residential urban density by type of municipality in 2011-14, 2015, 2019, and 2020. Distance by day per capita: (Trafikanalys & Statistics Sweden, 2014b, 2016c, 2020b, 2021b). Land use: (Statistics Sweden, 2018)

At the level of Sweden, we see similar relations with the data from Trafikanalys and Statistics Sweden (2014b, 2016c, 2020b, 2021b) by type of municipality (Figure S44). They vary depending on the year. For example, metropolitan municipalities have the shortest distances in all years, but in 2011-14 they have the same distance as large cities in 2020. The relationship between density and distance is not strongly defined due to the variability of the curve for different years and the uncertainty in the same year. Other characteristics might affect the distance travelled, such as income, size of the municipality, distance to other cities, the uncertainty of the survey, etc.

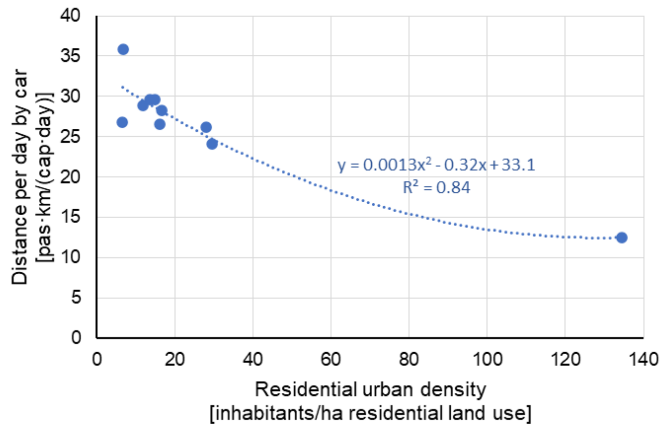

Figure S45 Distance traveled by car per capita by residential urban density by type of municipality (2015)

This function explains only the current situation. Further improvements for decreasing the distance travelled could be made by changing culture or social arrangements. To do so, we can examine the purposes of travelling. Cars are mainly used for work and leisure. Each of those reasons represents at least 30% of the distance run by car (Figure S46). In the case of the largest cities, the lower use in daily life, given the existence of public transport, is offset by the more intense use on weekends for travelling to natural areas that are lacking in urban areas. Because of this, some scholars do not see densification as an effective measure for decreasing transport impacts (Echenique et al., 2012). However, the long distances travelled for leisure might be compensated by the higher occupation rate at weekends for longer distance trips in comparison to daily commuting (more pas·km for the same veh·km). Still, cultural changes such as travelling less for leisure could be simpler than those which require material investments, such as increasing the frequency and outreach of public transport on weekends. Moreover, one of the results of increased densification is the reduction of the distance between natural areas and the dense urban core when the surrounding suburban sprawl is converted to parks or other kinds of natural areas.

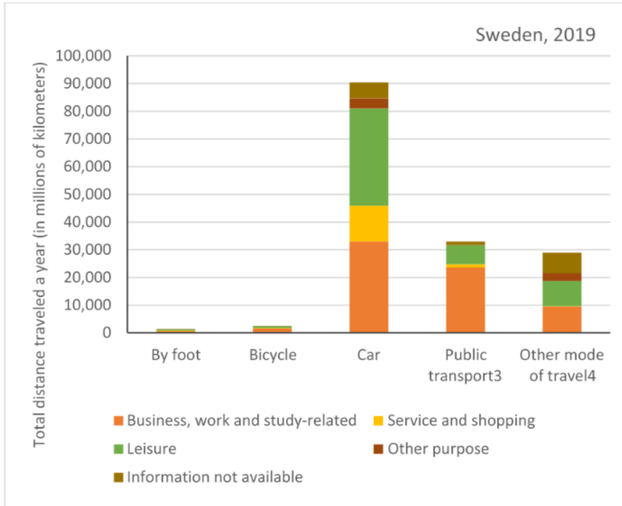

Figure S46 Total distance travelled a year in Sweden (2019) by mode of transport and the main purpose of the journey (Trafikanalys & Statistics Sweden, 2020b)

(aj) Occupancy rate

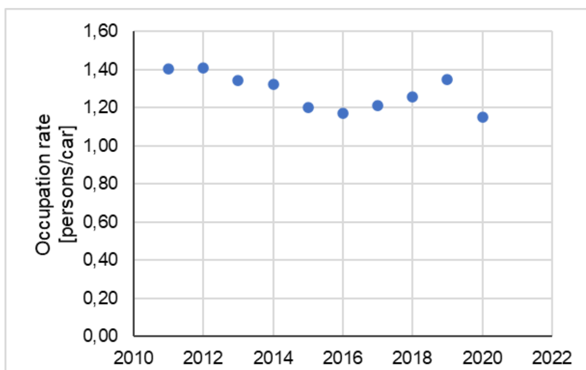

Figure S47 Occupation rate (distance run by people/distance run by cars) in Sweden (2011-2020)

The occupancy rate in Sweden has been calculated by dividing the pas·km travelled by people in Sweden (Trafikanalys & Statistics Sweden, 2014b, 2016b, 2016c, 2021b) by the veh·km (Trafikanalys & Statistics Sweden, 2021a). The data for 2020 comes from an exceptional year, considering the COVID-19 pandemic. We have taken 1.3 as a reference.

(ao) Correction distance per age of vehicle

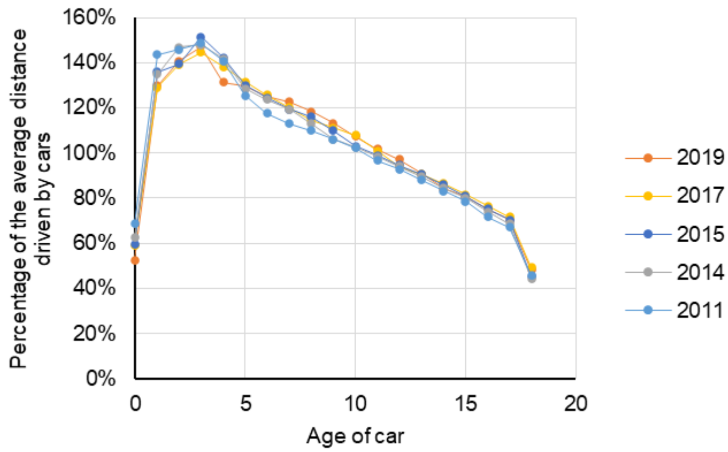

Figure S48 difference to average distance driven by cars by age of car (Trafikanalys & Statistics Sweden, 2013, 2014a, 2016a, 2018, 2020a). The maximum age in the x axis (18 years) refers to an open-ended interval of ages.

We have an average veh·km travelled by vehicle for each year. However, the distance run per vehicle depends on the age of the vehicle. The newer cars are usually used more intensively than older cars (Figure S48). The average distance run by vehicle is then adapted to the cohorts with a coefficient (Figure S49). The implementation of this correction is explained in the section *2.8. Distance run by cars*.

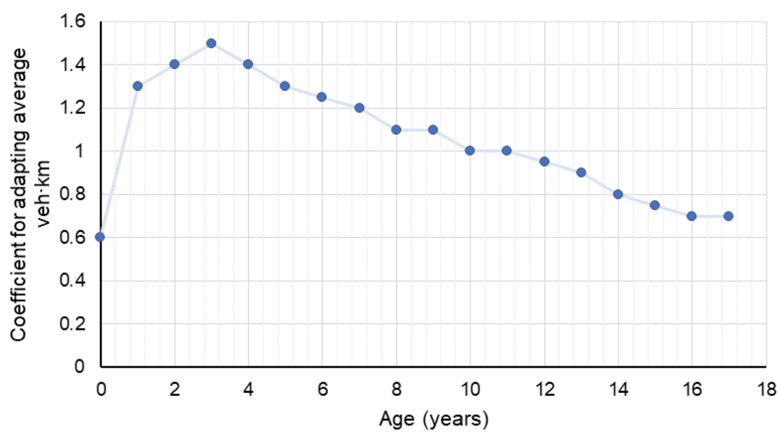

Figure S49 Coefficients for adapting average veh·km to the age of the vehicle

(ap) Fuel efficiency

Energy consumption is defined mainly by powertrain type and weight (Figure S50). To calculate the fuel efficiency, we made regressions of the data in Wolfram et al. (2020) in relation to curb weight (Figure S50). We assign the curve of diesel cars to natural gas and flex-fuel vehicles.

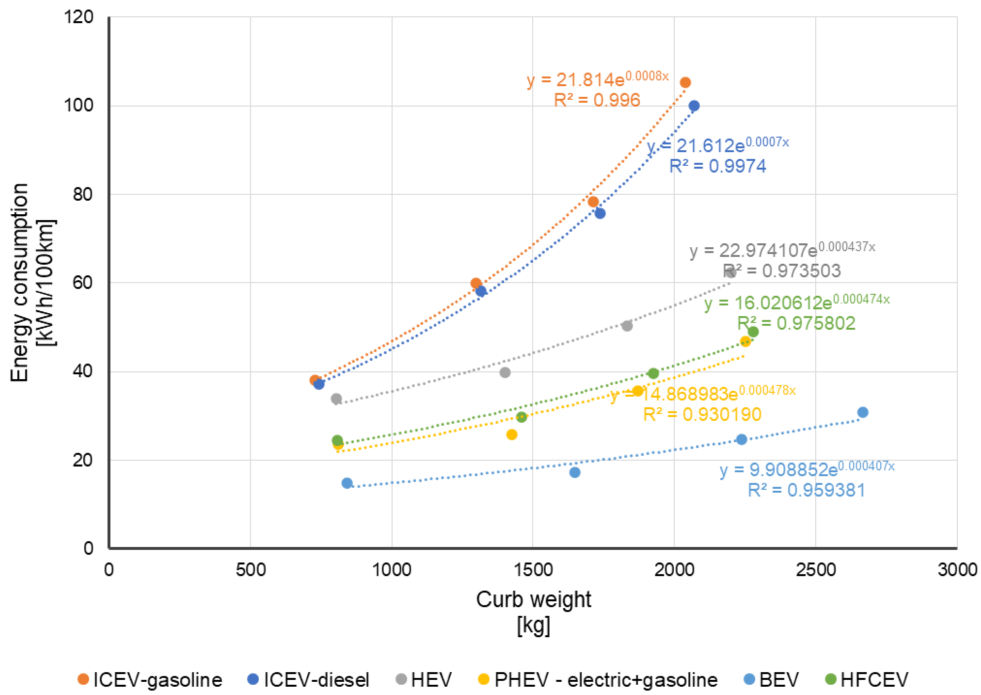

Figure S50 Fuel economy of different types of powertrains by curb weight. Derived from (Wolfram et al., 2020)

(aq) Correction of fuel efficiency for age

Age influences energy consumption both for the aging process and the different technologies. Older cars do not follow these trends. Weight decreases to around 1000kg (*(ae) Size of cars*), but fuel economy stays at 100-90kWh/100km (Schipper, 1995). In Figure S51, we can see the data from Wolfram et al. (2020) from Figure S50 plus historical data from Schipper (1995) (average new cars in Sweden, mostly gasoline) and Danilecki, Mrozik, and Smurawski (2017) (Volkswagen Golf MK).

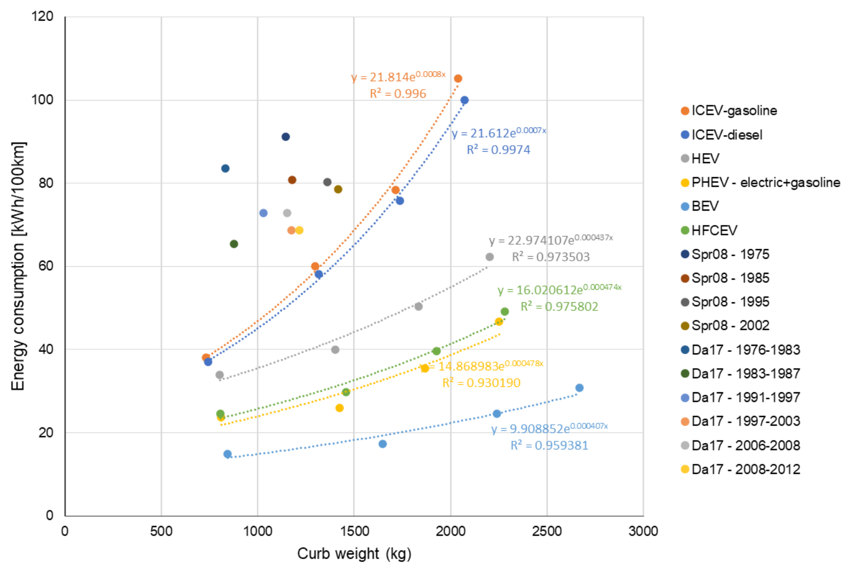

Figure S51 Fuel economy of different types of powertrains by curb weight. Data by powertrain type by (Wolfram et al., 2020). Historical data from Sweden's average new cars from Sprei et al. 2008 (Spr08) and historical data from Volkswagen Golf MK from Danilecki, Mrozik, and Smurawski 2017 (Da17)

We include a coefficient for the cohorts between 1985-2002 to multiply by the fuel efficiencies calculated with the equations to address the age impact. Before 2002, most vehicles were, in fact powered by gasoline (Figure S42). Therefore, we estimated the fuel consumption with the equation for gasoline cars in Figure S50. We divided the actual fuel consumption found in Schipper (1995) and Sprei et al. (2008) by the calculated fuel consumption according to Wolfram et al. (2020) to adapt the fuel efficiency of older cohorts.

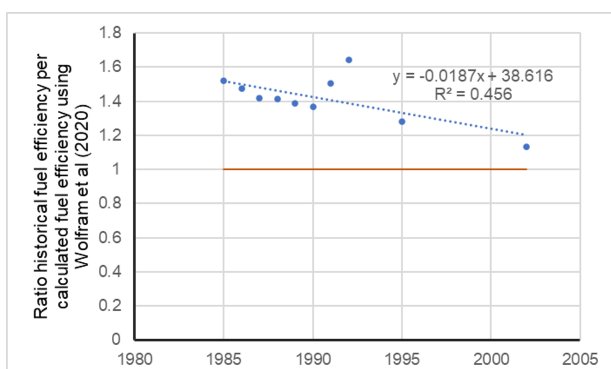

Figure S52 Ratio of historical fuel efficiency divided by the calculated fuel efficiency using the regressions derived from data in Wolfram et al. (2020) (1985-2001)

(ar) Allocation energy carriers

With these fuel efficiencies and the distance run by cars, we can calculate the energy consumption of cars as explained in GHG emissions of car use. However, we must calculate in which energy carriers this energy is consumed. To do so, we match categories of the powertrain types to energy carriers (Table S3).

Table S3 Allocation of energy carriers according to powertrain type

Powertrain/energy carrier	gasoline	diesel	electricity	hydrogen	natural gas	biogasoline	biodiesel
Gasoline	0.95					0.05	
Diesel		0.95					0.05
Hybrid	0.95					0.05	
Plug-in hybrid	0.8		0.3				
Electric_FC			1				
Natural Gas					1		
Flex-fuel						0.3	0.7

(at) Emission intensity – fuel use

We use the emission intensities in the IPCC national inventories for Sweden in 2017 (update 2019) in table 1.A.3bi.Cars (Naturvårdsverket, 2019) (Figure S53).

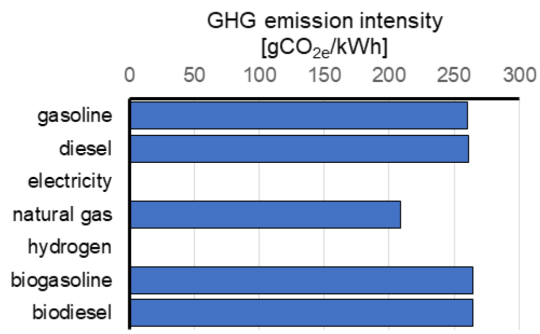

Figure S53 Emission factors of direct fuel use (Naturvårdsverket, 2019)

(av) Emission intensity – well-to-pump

The emissions from the extraction and refining of oil come from (Morfeldt et al., 2021), whose sources are (Jing et al., 2020; Masnadi et al., 2018). For natural gas: (Tong et al., 2015). For biogasoline and biodiesel they are retrieved from the Covenant of Mayors Default Emission Factors (Koffi et al., 2017), by subtracting the direct standard emissions to the LCA (2008-2015).

The electricity background system in the years 1990-2020 is retrieved from EEA (2021). This electricity mix is very low carbon already in the Nordic countries. The electricity mix is key in the assessment of the emissions of BEV vehicles (Ellingsen et al., 2016; Marmiroli et al., 2018; Mendoza Beltran et al., 2020; Wolfram et al., 2020; Wolfram & Wiedmann, 2017).

Fossil fuels will become scarcer and more difficult to extract and refine in time. Even though there could be technical improvements, the emissions are likely to increase. We use as a reference the current emissions in Venezuela from Jing et al (2020) as a reference for a less conventional oil that will be the reference in the future. We establish a linear trend to 2050. For electricity, we consider that it will reach 0 gCO_{2e}/kWh by 2050. We keep constant the biogasoline and biodiesel fuel cycle emission intensity during all the time interval of analysis. The complete evolution of the emission intensities is plotted in Figure S54.

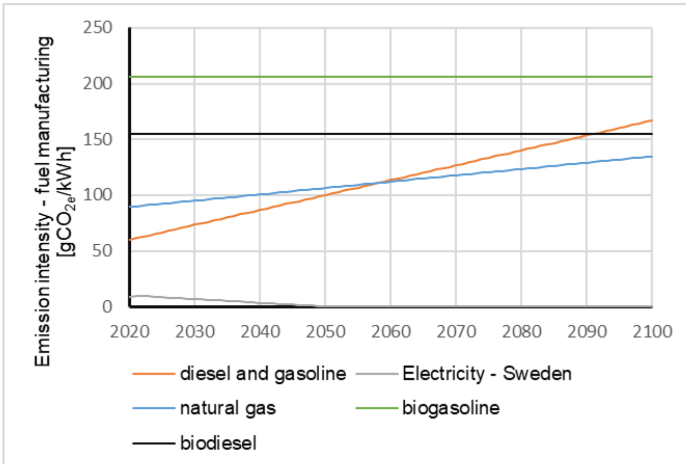

Figure S54 Future modelled trends of emission intensity for fuel manufacturing (2020-2100)

4. Scenarios

4.1. Initial conditions

	People per municipality	Population			Local employment	Residential urban density	Mobility		Residential size of municipality ("radius")		
							Cars per capita	Distance run by car per capita and day	Dense core	Total	
	1000 inh/mun	1000s	% of Swedish pop.	% in multi-dwelling buildings	% workers by working age pop	inh/ha	car/cap	pas·km/ (cap·day)	km	km	% of suburb
SKL01 metropolitan municipalities	598	1794	18%	79%	95%	134	0,36	13	2,30	3,0	23%
SKL02 suburban municipalities	**43**	**1618**	**16%**	**42%**	**60%**	**30**	**0,44**	**24**	**0,61**	**2,1**	**71%**
SKL03 large cities	**95**	**2940**	**30%**	**50%**	**79%**	**28**	**0,47**	**26**	**1,08**	**3,1**	**65%**
uburban municipalities to large cities	**15**	**332**	**3%**	**24%**	**51%**	**17**	**0,54**	**28**	**0,36**	**1,7**	**78%**
SKL05 commuter municipalities	**14**	**717**	**7%**	**29%**	**62%**	**15**	**0,54**	**30**	**0,37**	**1,7**	**78%**
)6 tourism and travel industry municipalities	15	292	3%	27%	74%	7	0,58	27	0,44	2,6	83%
SKL07 manufacturing municipalities	**15**	**810**	**8%**	**31%**	**76%**	**14**	**0,55**	**30**	**0,43**	**1,8**	**76%**
SKL08 sparsely populated municipalities	8	160	2%	23%	71%	7	0,60	36	0,34	1,9	82%
ipalities in densely populated regions	**25**	**868**	**9%**	**34%**	**70%**	**16**	**0,53**	**27**	**0,53**	**2,2**	**76%**
nunicipalities in sparsely populated regions	20	320	3%	32%	74%	12	0,58	29	0,53	2,3	77%
TOTAL SWEDEN	34	9851	100%	47%	76%	22	0,47	25	0,61	2,1	72%

Figure S55 Characteristics of the municipality types in 2015. The radius of municipality refers to the simplified model of residential area depicted in Figure S56.

Daily mobility works mainly at the municipal or metropolitan level. Therefore, we divide the country according to the municipality classification (2011 classification). Figure S55 shows some key characteristics of the municipality types, including population, employment, car ownership and distance run and simplified radius of the municipality. This radius is calculated for residential land use with a dense core (multifamily buildings) and a suburban sprawl ring (single-family houses) as in Figure S56. Many land uses are not included in this calculation (transport, services, industry, etc.) and thus we are not indicating the full distances in the table.

We do not include all kinds of municipality in the scenarios. On the one hand, metropolitan cities are already dense, and their trends go towards further densification. On the other hand, rural areas are eminently low density. There, changes in building types do not enable the implementation of public transport systems. There are fundamental economic activities where low-density rural areas play a major role, generally related to biomass (agriculture and forestry) and mining. Even though we do not aim to change the urban form of all kinds of municipalities in the model, we include 74% of population in the densification scenarios, which affect the following municipality types:

- SKL02 suburban municipalities (38 municipalities)
- SKL03 large cities (31 municipalities)
- SKL04 suburban municipalities to large cities (22 municipalities)

- SKL05 commuter municipalities (51 municipalities)
- SKL07 manufacturing municipalities (54 municipalities)
- SKL09 municipalities in densely populated regions (35 municipalities)

Some of these municipality types show clear suburban characteristics. Employment can show the residential "monofunctionality" of some municipality types. In these cases, citizens must travel to close larger towns on a daily basis for work and services. For example, *SKL04 Suburban municipalities to large cities* have only 51% of workers compared to the working age population, the lowest value of all municipality types.

Large cities, which are the centres of regions and might allocate services and work (second largest share of workers divided by working age group: 79%), have at the same time a relative low density (28 inh/ha), very far from metropolitan cities (138 inh/ha).

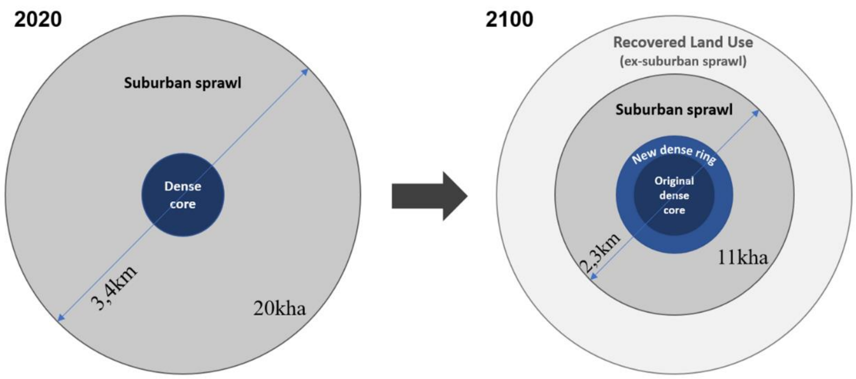

Figure S56 Example of changes in land use by densification of an ideal circular shaped municipality type with a dense core surrounded by suburban sprawl. This simplified model includes residential land uses only. Transport land use has potentially a large impact in the Land Uses and even more in suburban sprawl. New suburban sprawl will require further transport land use, while densification takes the existent transport land use.

4.2. Main scenario

Densification scenarios	built environment	
	k - type of new dwellings	*g - Lifetime houses*
Accelerated dens.	100% apartments	shorter
Slow densification	100% apartments	longer
Current values	current values	longer

Figure S57 Main scenarios for the paper: densification of the residential built environment

First, we assess the 3 main scenarios, which are related to changes in the built environment and the speed of the changes. These are related to the substitution of single-family houses per apartment buildings. Only two exogenous inputs change in the model: *(k) Type of new buildings*, and *(g) Lifetimes of single-family houses*. These three scenarios and two inputs are described in Figure S57: *current values*, *slow densification* and *accelerated densification*. *Current values* includes the current percentages of construction of houses and apartments and a rather long lifetime of houses. *Slow densification* would make that all new construction in the target municipalities are apartment buildings in order to densify. *Accelerated densification* would also shorten the lifetime of houses, making the process faster at the expense of underuse of the embodied resources in the existent built environment.

For the municipality types that are not affected by the densification scenarios, we produce another scenario that follows mainly the *current values* scenario.

4.2.1 Storylines

Accelerated densification:

Governments and companies make huge investments rebuild whole parts of cities. This entails that half of the single-family houses convert to apartments even if they have not arrived at their maximum technical lifetime. Cities become more mixed and dense, and this has important effects in both mobility and heating (possibility of installing district heating systems).

This scenario does not entail a win-win situation, but a high up-front investment that will give (or not) returns in the medium and long term. This is not compatible with a sudden decrease of GHG emissions but would enable more sustainable lifestyles in other spheres of daily life (e.g., shareability, product-services). We do not assess the monetary implications of these huge investments. This is key considering the weight of housing in the economy and in family budgets. Here, we only aim to make a first assessment of the trade-off in terms of emissions of the investment in built environment that enables changes in mobility patterns.

The higher density of demand provided by the housing density generates proximity if the urban design considers mixed uses, diversity, street design, etc. This decreases car dependency. It would also enable new alternative activities: increase collective spaces, shareability of devices (e.g., carsharing and carpooling: increasing car occupancy), increase social interaction. These futures are difficult to quantify because these are not current practices, but a future with more environmental and resource constraints could increase awareness and increase their acceptability.

Slow densification:

In this case, the new built environment consists only of apartment buildings, but following the technical obsolescence of the current stock to the end of their lifetimes.

Current trends:

This scenario is the one that follows the most the current trends. In this case, new built environment follows the shares in 2020, with more apartment buildings that houses, and follows the longer expected lifetimes.

4.2.2. Exogenous inputs in the main scenario

(g) Lifetimes of single-family houses

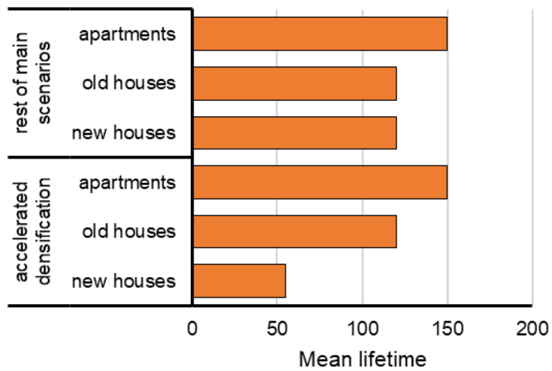

Figure S58 Scale of the survival curve of dwellings in the model by scenario

The lifetime of new single-family houses is the main input in this model for the scenarios. Together with *(k) type of new buildings*, we can model processes of densification. As it is explained in section *2.3. Stock-driven Product Flow Analyses houses and apartment buildings*, in fact, we have two stock-driven models, differentiating between houses and apartments. Both follow survival curves with normal distributions. The standard deviation is set as 0.25 times the mean.

In *accelerated densification*, we assume a premature demolition of single-family houses that have not reached yet their technical obsolescence. We differentiate houses built before and after 1950. Suburban sprawl with large areas of detached single-family houses started in the middle of the 20th century (Hayden, 1984). This is set in the different *(u) Floor Space Index* pre- and post-1950s (Figure S30). *Accelerated densification* has a drop of the lifetime of these post-1950 newer houses.

We do not have data for lifetime of the housing stock in Sweden. This is challenging to define since building stocks have been built basically during the 20th century and they are long lasting. Therefore, their end-of-life has not arrived yet for most of the stock. Moreover, historic buildings follow different trends. They have long lifetimes and are expected to be maintained for cultural reasons. The oldest cohort is set to be 100% maintained during the period of analysis.

Quantitative analysis for building lifetimes is lacking in literature. However, general consensus ranges from 50 to 100 years but it is different between countries (Aksözen et al., 2017; Aktas &

Bilec, 2012; Sandberg et al., 2016). For example, Aktas and Bilec (2012) estimated that in the US the average residential building lifetime was 61 years (with a standard deviation of 25 years). In Japan, the half-life of wooden and non-wooden buildings is different and also depends on the decade, being 63 years from 1997 to 2020 for wooden, and 52 years from 1991 to 2020 for non-wooden (Kayo & Tonosaki, 2022).

(k) Type of new buildings

The objective of the implementation of the model is to increase the density of residential areas. Therefore, new buildings in some of the scenarios will be apartment buildings and no new single-family houses will be built. The BAU trend of the last years in Sweden also includes large shares of apartment buildings and, therefore, a densification. The key aspect thus is not the share of new apartments, but the speed of construction apartments and early demolishing of houses.

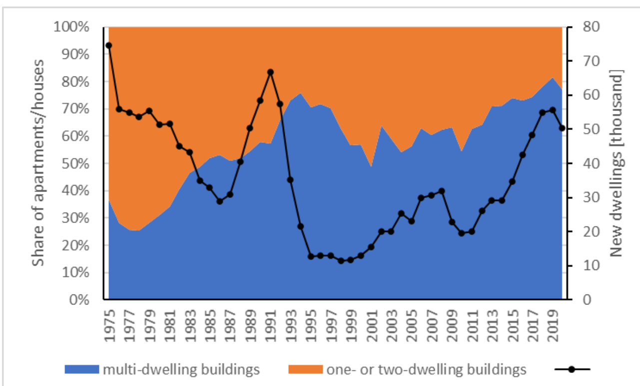

Figure S59 Completed buildings in newly constructed buildings by region, type of buildings and year in Sweden (Statistics Sweden, 2021b)

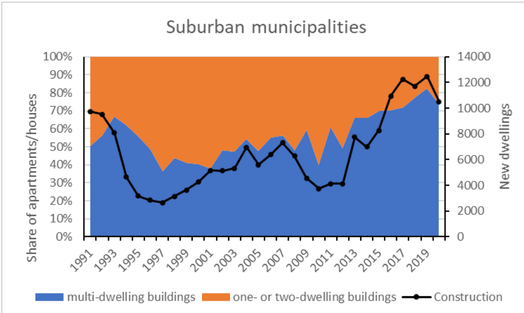

Figure S60 Completed buildings in newly constructed buildings by region, type of buildings and year in Suburban municipalities (Statistics Sweden, 2021a)

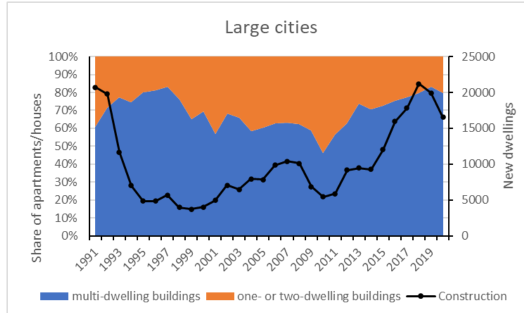

Figure S61 Completed buildings in newly constructed buildings by region, type of buildings and year in Large cities (Statistics Sweden, 2021a)

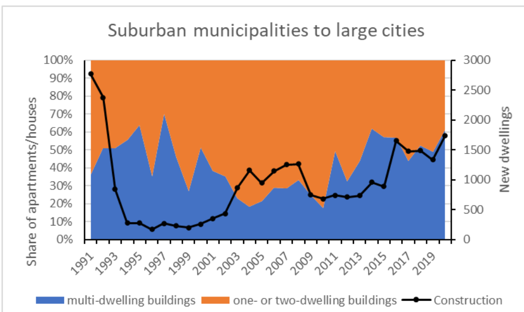

Figure S62 Completed buildings in newly constructed buildings by region, type of buildings and year in Suburban municipalities to large cities (Statistics Sweden, 2021a)

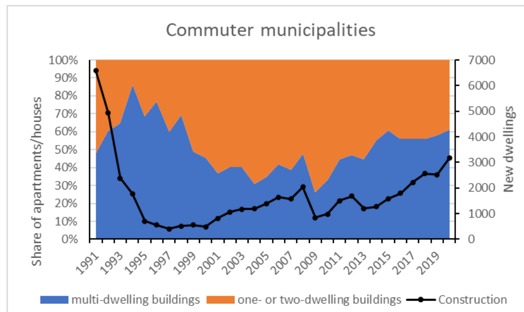

Figure S63 Completed buildings in newly constructed buildings by region, type of buildings and year in Commuter municipalities (Statistics Sweden, 2021a)

All new buildings are apartment buildings in *slow* and *accelerated densification* scenarios, whereas *current values* refer to the shares in 2021 (Statistics Sweden, 2021a) (Figure S64).

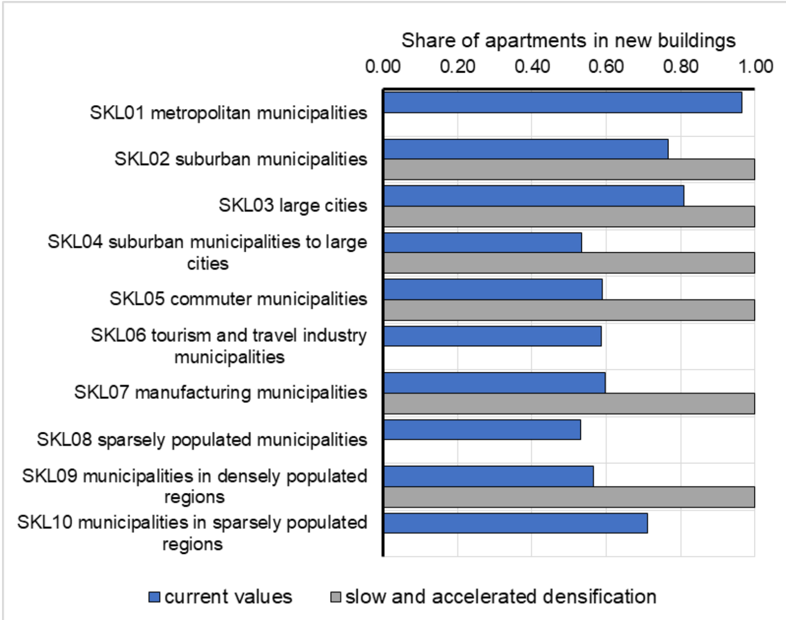

Figure S64 Share of apartments in new buildings according to the three main scenarios.

4.3. Sensitivity analysis

		Main scenarios	Sensitivity parameters			
			Longer lifetime of buildings	More intensive use	EU electricity mix	Non-electrified fleets
Families	*Household size (b)*	current values	current values	larger	current values	current values
Lifetime buildings	*Lifetime flats and houses (f and g)*	densification scenarios	longer	densification scenarios	densification scenarios	densification scenarios
Cars	*Occupancy rate (am)*	current values	current values	larger	current values	current values
	Size of cars (ae)	current values	current values	smaller	current values	current values
	Type of powertrain of new cars (af)	all BEV by 2030	all BEV by 2030	all BEV by 2030	all BEV by 2030	current powertrain shares
Electricity mix	*Emission intensity - fuel cycle/electricity mix (av)*	Sweden	Sweden	Sweden	EU	Sweden

Figure S65 sensitivity analysis of social changes, energy mix and electrification of the fleet, including the affected parameters. Lifetime of single-family houses changes according to each of the three densification scenarios.

Then, we can see the effects of these three main densification scenarios in four different contexts (i.e., we would have in total 3x5 possible futures to explore). These scenarios are *Longer lifetime of buildings*, *More intensive use*, the *EU energy mix* and *Non-electrified fleets*. The latter two sensitivity scenarios only affect GHG emissions and have the same service level as the main scenario.

4.3.1. Longer lifetime of buildings

The first one analyses the effects of a longer lifetime since the durability/mortality of the buildings is one of the most uncertain inputs, with little availability of benchmarks in the literature. The input that is affected is *(g) Lifetimes of single-family houses* (Figure S66).

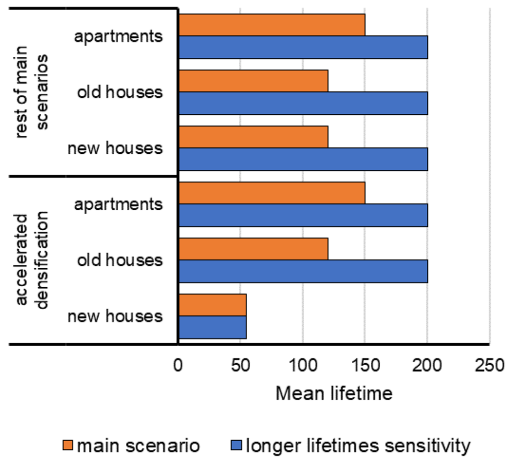

Figure S66 Scale of the survival curve of dwellings in the model by scenario

4.3.2. More intensive use

More intensive use directly affects residential density and service level at low or no-investment costs. These could be considered "social changes" since they depend on the decisions of household units, but the auto industry should also provide smaller cars. This scenario also expects larger household sizes following cultural changes and the fact that population growth is fuelled by migration. Migrants use to live in larger households than Swedish. This decreases the number of dwellings that are necessary.

(b) Household size (inh/HH)

Household size is different between types of municipality and types of dwelling (Figure S67). The household size has not changed much in the last 30 years in the municipalities (Figure S68), and the average of Sweden has been 2.1 people/household during the whole 1990-2021 period. Metropolitan municipalities have increased from 1.8 to 2 people/household. In some of the smallest municipality types, the household size has decreased to be the lowest in Sweden: 1.8-1.9 in 2021 for Tourism and travel industry municipalities, Manufacturing municipalities and Municipalities in sparsely populated regions.

The *More intensive use* context increases slightly the occupation of dwellings in each municipality type (Figure S70). This brings the average of Sweden to 2.5 people/household, similar to countries like Portugal and Spain (Figure S69).

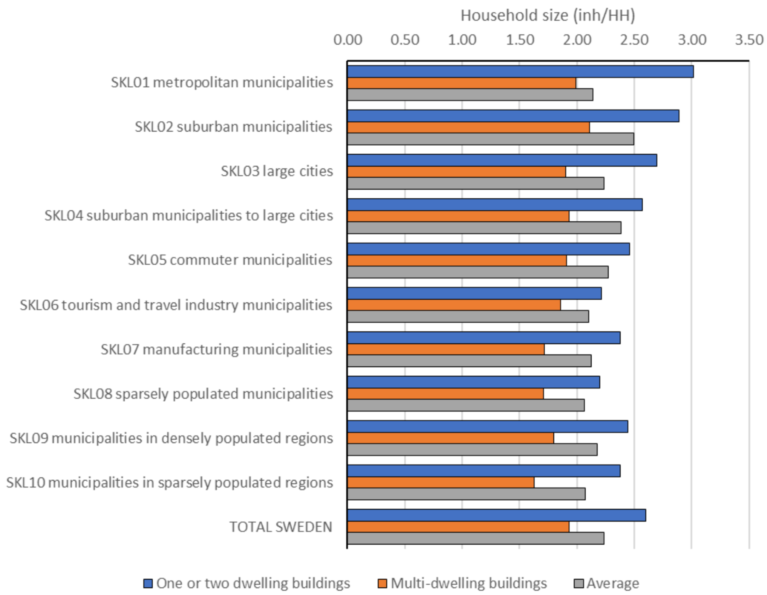

Figure S67 Household size by municipality and dwelling type (2015) (Statistics Sweden, 2020b, 2021e)

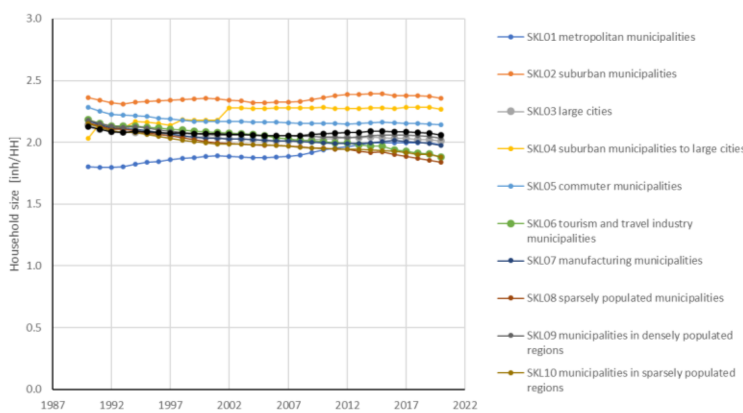

Figure S68 Household size by municipality type (1990-2021) (Statistics Sweden, 2021d, 2022a)

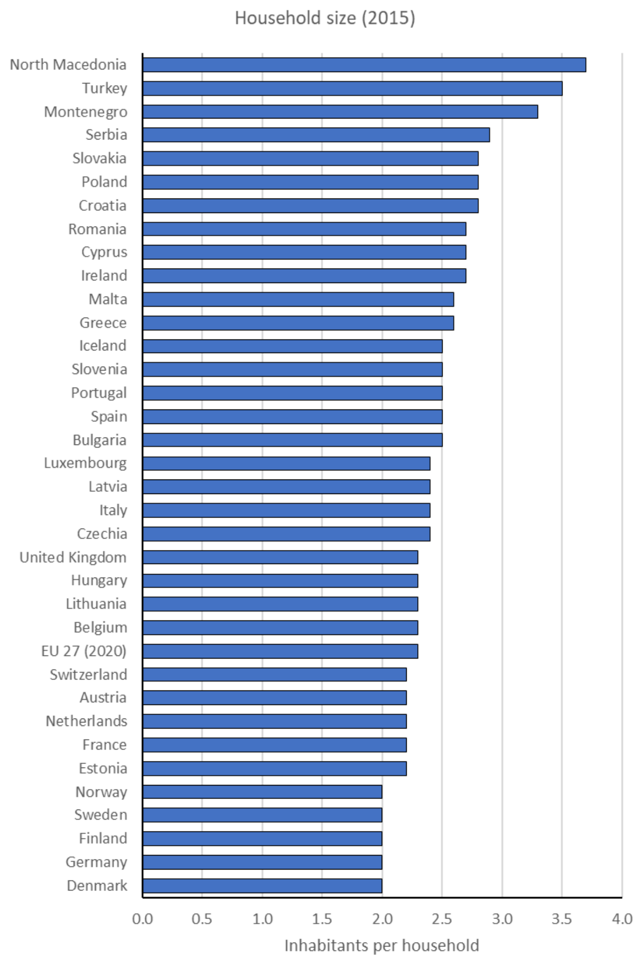

Figure S69 Average household size of European countries (2015) (Eurostat, 2022a)

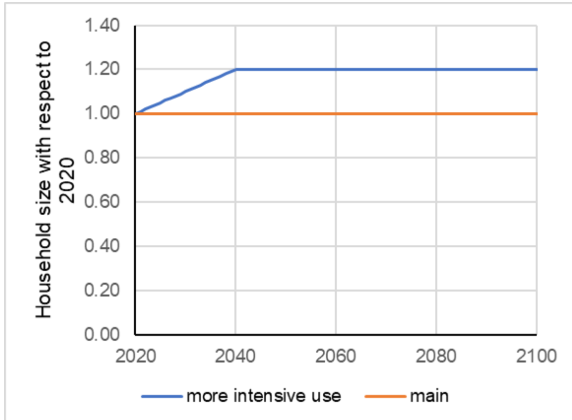

Figure S70 Scenarios for household size to apply to every municipality type

(ae) Size of new cars

The size of cars is a key parameter for material use and thus production resource use, but also for fuel efficiency. It has increased over the years both in the average value of new cars in European countries, within car segments and powertrain types (ICCT, 2021). Sweden has the largest cars in Europe by mass in running order (kg) (ICCT, 2021).

Electric and electrified cars are heavier. Sweden has the largest % of new registrations of hybrids (22.6%) and 9.6% of battery electric/fuel cells in 2022. The Netherlands has a way lower average mass, but rapidly increasing. Now they have a 20.5% of new registrations that are electric or fuel cell (2020).

Despite this upward trend, we define the scenarios in two different directions: "*More intensive use*" entails a decrease in the average weight of cars, while the rest of scenarios consider a constant value following the last year of the historical time series.

Mass is different for every powertrain, but since 2030 only electric cars enter the stock in the scenarios related to electrification, Figure S71 shows only electric cars as a reference. The changes are in scenario "*more intensive use*", where size decreases linearly to 2035. For example, gasoline and diesel cars decrease to the level of current new cars in Italy (slightly above 1300kg/car, larger than small and mini cars). The rest of scenarios have constant values. The post-2035 (scenario "more intensive use") and constant values (rest of scenarios) are shown in Figure S72.

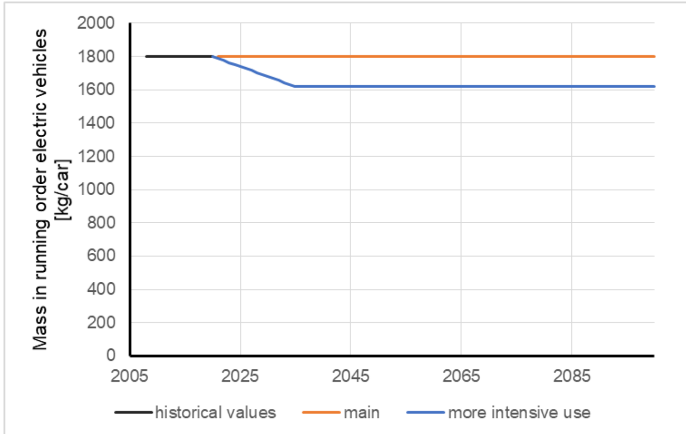

Figure S71 sensitivity scenarios for weight of new cars – electric vehicles (2020-2100)

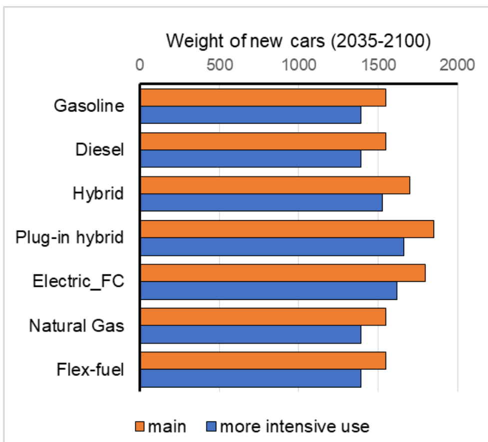

Figure S72 scenarios for weight of new cars (2035-2100) for each powertrain type

(am) occupancy rate

More intensive use includes a linear increase in occupancy rate from 1.3 to 1.8 in 2035, as shown in Figure S73.

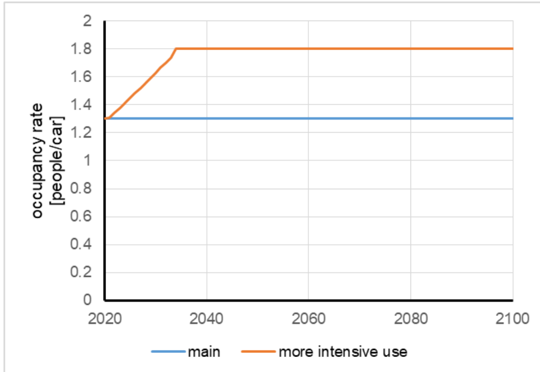

Figure S73 occupancy rate for sensitivity analysis

4.3.3. EU electricity mix

The electricity mix has been flagged as one of the main parameters affecting the carbon footprint of electric vehicles. In this scenario, we include the EU electricity mix in 2020 with a linear trend of decarbonization.

(av) emission intensity – fuel cycle/electricity mix

The electricity mix is one of the key parameters of the emission footprint of electric vehicles. In the main scenario we assume an effective ban of vehicles other than BEV by 2030 with the Swedish electricity mix, which is already low-carbon. Here, we assess the effect of the EU electricity mix, but with a linear decarbonization to 2060.

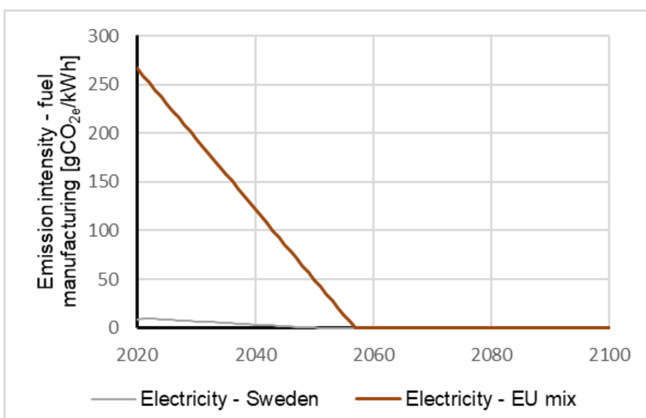

Figure S74 Emission intensity electricity mix sensitivity analysis

4.3.4. Non-electrified car fleets

We include a context that uses the 2020 powertrain shares of new cars as the values for the whole time series. Therefore, car fleets will not be electrified and will maintain a variety of powertrain types.

(af) Powertrain type

The goal of European governments is to electrify passenger car fleets. However, this is not intensively implemented now. Electrification is produced mostly in the form of Plug-in-hybrids nowadays, which still only represented 22.6% of new registrations in 2022 (Figure S40). Battery electric vehicles were only a 9.6% of the new registrations in 2020.

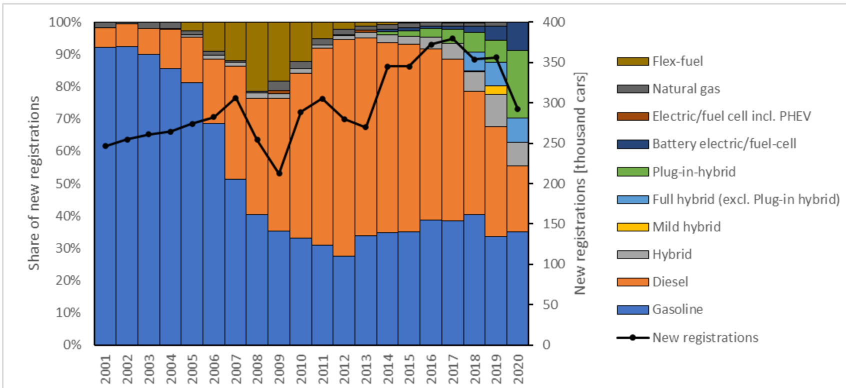

Figure S75 New registrations and share of powertrain of new registrations in Sweden (2001-2020) (ICCT, 2021)

For the main scenarios, we consider that only electric cars are produced from 2030 onwards. Until then, the rest of vehicle types decrease linearly to 2030 and electric cars fulfil the rest of the demand. In the sensitivity context, the shares of powertrains in new cars from 2020 are set as constant for the whole time series (Figure S76).

Morfeldt et at (2021) in a model for the Swedish vehicle fleet to 2050 shows that "a ban in 2030 is not sufficient for reaching Swedish climate goals for 2030" (p.1). Here we are playing with a model that will not reach the emission goals. The objective of the model is to explore the potential role of densification, and we are not considering drastic changes in the background system.

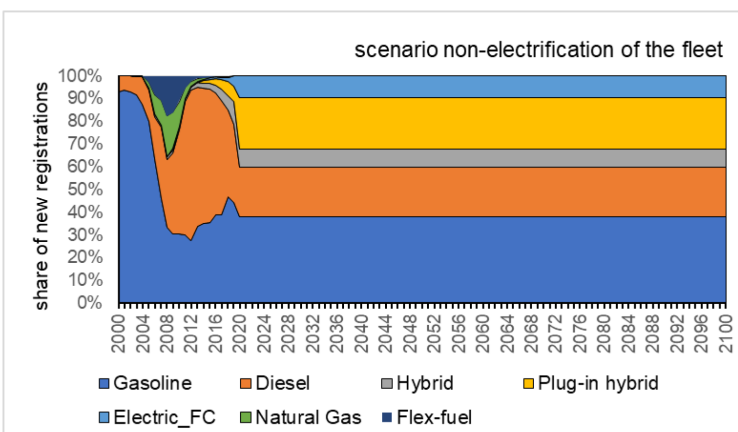

Figure S76 Share of powertrain type of new registrations for Non-electrified fleets

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