SIGILLUM UNIVERSITATIS ISLANDIAE

Decarbonization Scenarios for Reykjavik’s passenger transport: The combined effects of behavioral changes and technological developments

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Executive summary

Decarbonization of passenger transport is one of the key means to reduce the global GHG emissions and stabilize the climate to an acceptable warming level. The emissions from the road transport sector relate to travel behaviors and the technologies, which are driven by policies, incentives and disincentives, and transport networks. Moreover, the overall emissions are not simply those caused within an urban region, but the sum of global production and delivery chain emissions of vehicles and fuels. Along with the electrification of the vehicle fleet, the importance of the production phase increases, as well as those of the local electricity system.

As is evident, the potential pathways to decarbonize the passenger transport sector are plenty, including the decarbonization of fuels, using more efficient vehicles, modifying urban design, and changes in travel patterns and mode shares. In this project we depict how changes in these components under different development scenarios can affect the GHG emissions in Reykjavik Capital Region. To give a holistic overview of different possible pathways, we defined seven decarbonization scenarios of future changes in the passenger transport of Reykjavik Capital Region, based on a comprehensive review of policy documents in the region and academic literature. Then, we assessed the implications of each scenario on direct and indirect GHG emissions using an analytical framework linking three models; the behavioral model, the energy system model for Iceland (UniSyD_IS), and the Excel-based GHG emissions estimator. We used a socio-technical approach to qualitatively describe the scenarios through writing plausible storylines. Each scenario is defined by the level of changes in four components; urban structure, technologies, policies and lifestyle. In our perspective, the future development of these four drivers will determine how the passenger transport in Reykjavik Capital Region might look in 2050. The time-span was split into short-term 2020-2030, mid-term 2030-2040 and long-term 2040-2050.

Based on the identified components, decarbonization scenarios can be briefly described as:

- **S1. Business-as-usual (BAU)**, used as a reference scenario, following the targets set by the cities in the region and the regional administration, in two variants:
  - **S1a. BAU without changes in travel behavior**, based on conservative assumptions of the regional master plan, where projects described in the plan are realized, but travel behavior does not change or changes minimally.
  - **S1b. BAU with changes in travel behavior**, based on more optimistic predictions of the regional master plan, where projects described in the plan are implemented and resulted in changes in travel behavior.
- **S2. Urban structural change (USC)**: includes strong focus on land-use and transportation plans and policies aimed at public transportation improvement, transit-oriented development, densification, and improving conditions for walking and cycling, without significant changes in lifestyles.
- **S3. Urban structural change + Lifestyle change (USC+LS):** refers to the situation that the strong focus on land-use and transportation plans (public transportation improvement, transit-oriented development, densification, and improving conditions for walking and cycling), combined with strong demand-side policies (to reduce the use of private car) resulted in significant changes in lifestyles.

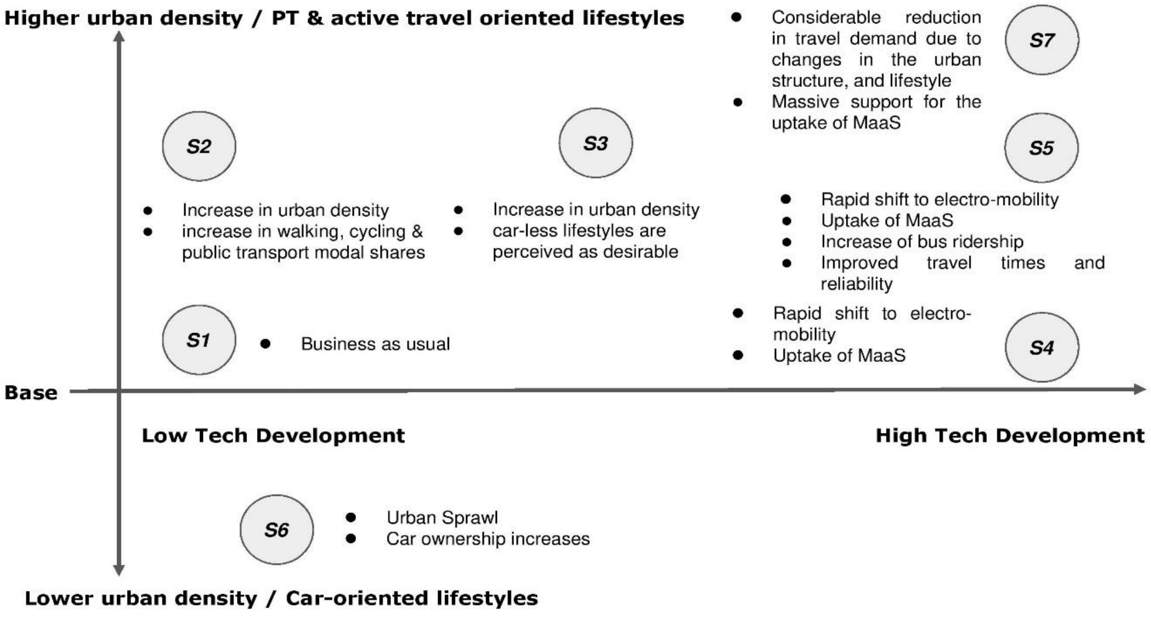
S4. Technological change (Tech): with strong policies aimed at transport electrification (rapid adoption of EVs and electric buses) and digitized mobility solutions (mobility as a service, MaaS), that have a notable potential to reduce both emissions and kilometers travelled by private cars.

S5. Integrated Approach (IA): The world and the region grasp the problem of climate change, act accordingly, and changes in both technologies and lifestyles combine and together bring significant decarbonization effects.

S6. Worst case (WC): the-warmer-the-better, presuming macro-scale developments pushing global and regional politics away from decarbonization targets, with weak or no development towards GHG reductions in any aspect, globally or locally.

S7. Radical Change (RC): describes a state that climate change become an imminent threat and countries must take the responsibility for the emissions occurring within their national boundaries, as well as for the indirect emissions occurring due to the use of imported goods and services. At the urban level, there will be strong restrictions to private car use, fiscal disincentives to possessing and operating vehicles, and strong support for MaaS, public transport and active modes of travel.

Figure illustrates the position of scenarios on the two axes of urban density/Public transport and active travel oriented lifestyle and technology development.



To estimate the associated direct and indirect GHG emissions for the scenarios described above, an analytical framework linking three models has been developed.

The behavioral model was utilized to quantify the changes in the driving factors for each scenario, while the UniSyD_IS model assessed the impacts of a set of policies on the transition to electro-mobility. Also, the UniSyD_IS model projected the composition of the passenger vehicle fleet and then estimated direct GHG emissions (Tank-to-Wheel) coming from each vehicle type. One of the key advancement of this analysis was the development of an excel-based model to calculate the indirect GHG emissions from the transport sector, focusing on the production and disposal of the different vehicle types. Based on the inputs from the behavioral and UniSyD_IS models, the excel based GHG emissions estimator, calculates the direct and indirect emissions for each scenario.

Both direct and indirect GHG emissions from passenger transport in Reykjavik Capital Region were assessed under all scenarios, and looked at separately, as well as the contribution of the different components listed above. In the BAU scenario, the total annual GHG emissions from passenger transport in Reykjavik Capital Region will be around 300 kt CO_2-eq in 2050, close to as they are currently. Along with easy behavioral changes (S1b), the total emissions would decrease only by 6.8%. Focusing on urban structural change (S4), it's possible to decrease the direct and indirect emissions by 25% and 23%, respectively. On the other hand, if we only enforce policies to support technological development (S6), we would be able to cut the direct emissions, but the indirect emissions would increase, mainly due to emissions from the production and disposal of vehicles. Thus, it can be concluded that only in the Integrated Approach (S5) and Radical Change (S7) Scenarios, in which a combination of policies are implemented simultaneously (increase urban density, induce lifestyle change and policies to support the electrification of the passenger vehicle and bus fleets, and reduction in private vehicle ownership), both direct and indirect GHG emissions can be reduced significantly.

Key Findings:

- The Radical Change scenario (S7) leads to the lowest annual emissions of 33 kt CO_2-eq by 2050, in comparison to 310 kt CO_2-eq in the BAU scenario and 490 kt CO_2-eq in the S3-Worst case scenario.
- Within the Radical Change scenario, the most influential factors are technological development (electrification of fleet) and the car ownership (driven by considerable growth in MaaS, public transport and radical development in urban structural form and behavior), accounting for 57% and 42% of the decrease in emissions, respectively.
- The direct emissions are the lowest in the Radical Change, Integrated Approach (S5) and technological scenario (S4) where the transition to an entirely electric vehicle fleet leads to a virtual zero direct GHG emissions.
- The technological scenario leads to the highest indirect emissions however, as it was assumed a high vehicle ownership rate would continue, and the emissions associated with producing a large number of EVs leads to high indirect emissions.
- The results clearly show that the key measure to significantly reduce indirect emissions is to reduce vehicle ownership by means of supporting MaaS and public transport.
- The most influential components having the strongest impact on the overall emissions are the electrification of the vehicle fleet and limiting car ownership.
- In the short-term, until 2030, the Radical Scenario outperforms all other scenarios, with the S5 and S3 scenarios being second best. In the long term the radical change scenario again far outperforms all other scenarios, and the S5 Integrated Approach scenario combining technological change, urban structural changes, and behavioral changes performs second best.
- The cumulative overall emissions until 2050 are 10,282 kt CO_2-eq in the BAU, 4,887 kt CO_2-eq in the Radical Change Scenario, and 12,482 kt CO_2-eq in the worst case scenario.

Disclaimer:

The authors of the report are responsible for its contents. The report and its findings should not be regarded as to reflect the Icelandic Road Authority's guidelines or policy

Table of Contents

Table of Figures

Introduction

Transportation is the core segment of urban development by facilitating access to education, markets, and other services (Pardo, et al, 2010). It is also one of the sectors with the highest climate change impact and sharply increasing global emission load but should go through a rapid decarbonization if we are to meet the 1.5 degree warming target (IPCC, 2018). The most notable urban transportation problems in Iceland are environmental impacts such as emissions of GHG, and the need to import fossil fuels (Rodrigue, 2013, Loftsdóttir, et al., 2014) in addition to the provision of infrastructures.

Over the next four decades, the transportation sector will face unprecedented challenges not only from an environmental but also from an economic and social perspective. GHG emissions from the combustion of fossil fuels, air quality and health, noise pollution, material consumption, mortality through road accidents, congestion, social exclusion, and employment rates are only some factors that are influenced by policies concerning mobility. These challenges will all be compounded by uncertainties emerging from government intervention and regulation. Regional and global cooperation, unstable global economic situations, and potential technological breakthroughs will all have a significant impact.

The target is sustainable transport in all the three fields: environmental, social and economic (UN2015). One of the key components in the environmental sustainability field is de-carbonization of the transport sector as a part of the quest for limiting global warming to 1.5 degrees celsius (IPCC 2018). Currently transport is responsible for 20% of the global greenhouse gas (GHG) emissions and is one of the sectors with the highest potential for mitigation (IPCC 2018).

Cities are considered as key governance-level bodies in policy-guiding towards a lower-carbon future (IPCC 2018). De-carbonization of passenger transport is one of the key target areas in cities' climate actions through the globe (C40 2018). They hold substantial power over several factors influencing the development of GHGs from transport, particularly those from passenger transport. Local governments can intervene in transportation systems and support innovations that influence these systems. At the same time, cities are subject to macro-scale political, economic, technological and social factors that may influence emissions from transport in a way compatible or incompatible with city level-policies. Local-level interventions and innovations and macro-scale developments together influence properties of transportation systems that are relevant for GHG emission levels.

City of Reykjavik District Plan for 2010-2030, established goals for reducing the emissions of GHGs by 73% before the year 2050, while aiming to become carbon neutral by 2040 (City of Reykjavík, 2016). Considering the significant use of renewable sources for power generation and space heating, the main focus will be on the transportation sector and it was projected that all busses and more than half of the city’s private cars will use sustainable and green energy sources in 2030. Therefore, in recent years the Icelandic government has introduced incentives such as tax exemptions and emission-differentiated vehicle taxes to promote the contribution of green vehicles in the transport sector (Alþingi, 2012). Several previous energy-system studies have addressed the effects of technology development, fuel supply-push policies, banning strategies, fuel prices, and a carbon tax on the evolution of Alternative Fuel Vehicles (AFVs) in Iceland (Shafiei, et al, 2012, Shafiei, et al, 2014, Shafiei, et al, 2015).

Two main knowledge gaps:

1. Most commonly considered are technological changes, and there is not enough knowledge on combined behavioral and technological. The combined effects of behavioral changes and technological progress in decarbonizing passenger transportation have been seldom studied globally, and never fully considered
2. Indirect emissions from transportation have seldom been taken into account in previous studies and policy documents. For instance, The City of Reykjavik Climate Policy states that “by 2040 emissions from automotive traffic and public transport will be free of greenhouse gases”, focusing only on the direct (or tailpipe) emissions, it will be unlikely for indirect (or life-cycle) emissions from transport, which can be significant, particularly if the transition to new technologies speeds up the car fleet renewal pace. Manufacturing vehicles and their batteries, transporting them to Iceland and disposing of them after use causes high GHG emissions in addition to their operation. Omitting these indirect emissions from a transition scenario assessment could mean very biased scenario outcomes. While the local emissions might appear low with a rapid transition to low-carbon vehicles, the overall global cumulative emission load could actually increase in comparison to a baseline situation without the transition to low-carbon vehicle technologies.

Project objectives

The fundamental purpose is to estimate GHG emissions of different transition scenarios focusing on the behavioral changes and technological developments using the Icelandic energy and transportation system model (UniSyD_IS).

The primary objectives are to:

1. Design multiple decarbonization scenarios focusing on changes in social mobility trends and rapid technological development
2. Estimate the changes in direct and indirect GHG emissions from the passenger travel in each scenario using the Icelandic energy and transportation system model

Background

In this section, we summarize the literature background on the main factors that influence critical variables in our scenarios (i.e., travel, demand, mode shares, car ownership, mobility as a service, and electric vehicle adoption rates). The factors include urban structure, lifestyles, policies and regulations, and available technologies.

Travel behavior variables: travel demand, mode shares

Urban structure

Compactness

Several studies have found a high correlation between transport energy use and density (e.g., Newman & Kenworthy, 1989; Newman et al., 2013; Ewing & Cervero, 2010). In their broad review of previous literature, Ewing & Cervero (2010) found that several factors from residential density to land-use diversity, public transport accessibility, and distance to the main city center all contribute to the overall compactness impact. This finding seems to hold even when the so-called residential self-selection, households selecting the residential location according to their travel needs and preferences, was taken into account. However, the self-selection phenomenon somewhat weakens the compactness effect. According to Ewing & Cervero (2010), typically, over 50% of the compactness impact on travel demand is due to the urban form.

Newman & Kenworthy (1989), in their famous study on the correlation between the built environment compactness and transport energy use, suggested a population density threshold of 3,000 inhabitants per square kilometer below which transport energy use starts growing exponentially. Between 3,000 and 9,000 inhabitants per square kilometer transport energy use still halves, but after 9,000 density only has an additional marginal impact.

Auto, transit and pedestrian-oriented urban forms

The urban structure affects car ownership rates, and via them, the distances driven and the modes chosen. The built environment causality has been shown in several studies, recently, e.g., in Cao et al. (2019) who summarize that:

> *"Change in the B.E. might lead to reduction in amount of car travel in at least two ways. First, the B.E. may create more conducive conditions for alternative means of transport and less conducive conditions for car travel, which can then induce a shift from auto-based to non-motorized and/or transit-based travel. This may lead to a reduction in car ownership. Second, the B.E. that promotes higher population density and land-use mix may reduce the overall amount of travel (VKT) by bringing origins and destinations closer together, although car ownership may not be necessarily reduced. Out of the two scenarios, the first one is more profound as it implies a strong shift in travel preferences."*

Figure 1 by Cao et al. 2019, presents the built environment causality.

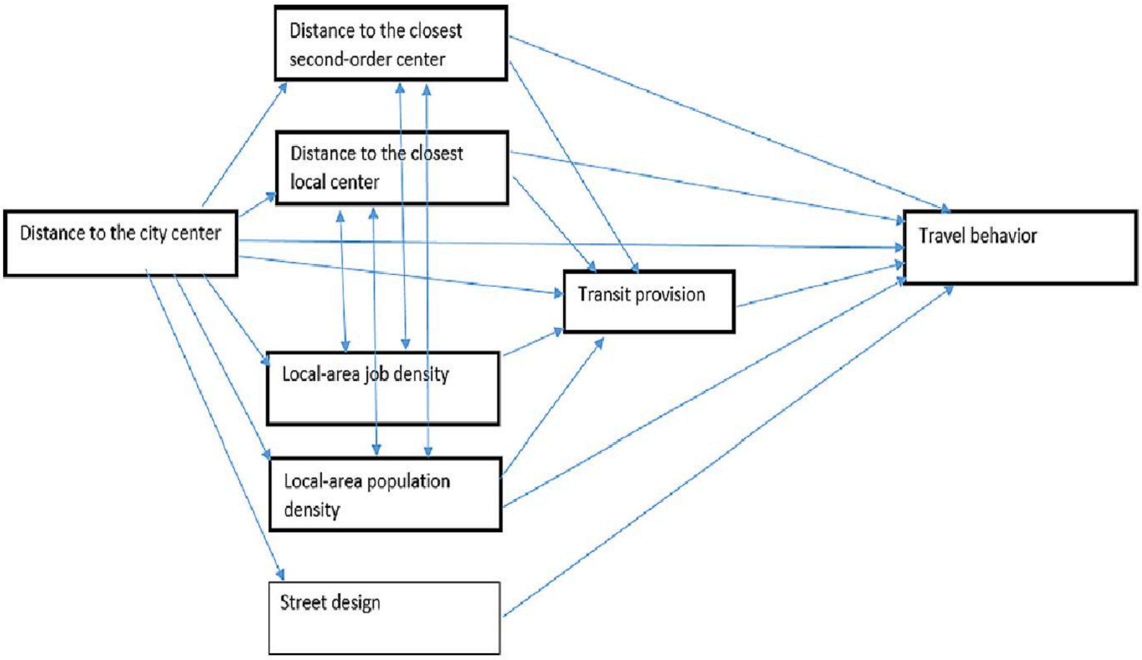


Figure 1: Causality between the built environment and car ownership

Some general urban structural qualities have been connected to auto, transit, and pedestrian-oriented urban forms. According to Newman et al. (2016), these qualities are:

1) Universal thresholds of >100 inh./ha = pedestrian; 35-100 = transit; <35 = auto
2) Universal one hour travel time budget for work-related travel, which leads to radius sizes of <2 km, <20 km, and <40 km for pedestrian, transit, and auto-oriented city structures.

They notice that all cities include areas belonging to each one of the three structures, but emphasize the importance of understanding these universal pre-conditions. Further they foresee polycentricity as the development direction when city-sizes grow and distances otherwise exceed the threshold radius sizes regardless the density.

Road capacity

Regardless of the suggested thresholds, it is not only density and distances, but road capacity plays a major role in shaping the dominant archetypes (McIntosh et al. 2014). More road capacity leads to improved auto conditions and increased usage, further demand for capacity, and as the final result a strong auto-orientation (Kenworthy 2018). Vice versa, residents of regions planned as pedestrian or transit have been found to start behaving according to the structure type (Newman et al. 2016; McIntosh et al. 2014). Creation of walking areas leads to further demand for them. As Newman et al. (2016) put it, "behavioral change follows the change in the urban fabric". McIntosh et al. (2014) quantified the connection with density and transit service kilometers, and found that an increase of 1% in both reduces VKT by 0.2% and 0.16% respectively. They also divide cities between motorization-oriented archetype and the traffic-limiting archetype, and found 49% lower car-use rates from the latter in comparison to the full motorization strategy cities.

Public transportation provision

Urban rail has been suggested as a critical factor in shaping transit-oriented structures (Kenworthy 2018; Newman et al. 2013). However, the impact seems to be strongly connected to the travel time factor (Newman et al. 2013; Bradley and Kenworthy 2012), and therefore bus rapid transfer (BRT) systems have also been found to be influential (Cervero 2013; Bradley and Kenworthy 2012), particularly BRT systems mimicking rail systems in rapidness and service frequency. Because plans for improvements in public transportation of the Capital Region primarily focus on the bus system expansion with Borgarlina, a kind of Bus Rapid Transit (BRT) system, we focus on the effect of such systems on travel demand and mode shares in cities.

Cervero (2013), based on a study including 105 global cities with BRTs, promote the BRT solution as the most suitable particularly for smaller cities. Overall, *ceteris paribus*, if one can more easily access his/her desired destinations without a car, he/she is less likely to have one (Zegras 2010). The key is to make the other transport modes competitive. The newest and the most comprehensive review of BRT influence on travel behavior based on 86 cases worldwide (Ingvardson & Nielsen, 2018) reports that ridership changes (in the context of travel time reductions) and modal shifts in specific bus lines or transit corridors in which the systems were implemented strongly vary between cases. Bus ridership changes ranged from 4% in Seoul to 150% in Istanbul. Modal shift from cars was in all cases positive but varied significantly and ranged from 4-9% in Istanbul (Metrobus) to 40% in Adelaide (O-Bahn) (Ingvardson & Nielsen, 2018).

A few examples can be provided: 19% or 24% of the Orange Line passengers in Los Angeles switched from cars, depending on the data source (Ingvardson & Nielsen, 2018; Federal Transit Administration 2011). In three more comprehensive implementations of BRT systems in Bogota (TransMilenio), Mexico City (Metrobus), and Jakarta (TransJakarta), the modal shifts from car were much smaller, 2.4%, 6%, and 7%, respectively (Hook et al. 2010).

There are few sources on the BRT's influence on city-wide modal shares in the literature. One of the reasons might be that the holistic effect of BRT implementation might be difficult to disentangle from other developments. For instance, in Bogota the modal share of public transportation has decreased from 57% in 2005 to 39% in 2015 (61% of motorized trips) (Guzman et al., 2018). The decrease might be due to increases in motorization and shifts in demand towards walking and cycling that occur regardless of the BRT implementation. Even if a new BRT increases its spatial coverage to almost the entire city, time-space accessibility may continue to be constrained for people who use public transportation and thus city-wide shares may not increase or even decrease (Guzman et al., 2018).

The literature suggests what characteristics of the BRT implementation influence its performance and impact on travel behavior in specific corridors and city-wide. Travel time reduction is considered a primary factor. However, it is not the absolute rapidness or a speed threshold, but the relative time-competitiveness of public transport in comparison to cars which matters (Bradley and Kenworthy 2012). In a typical situation, buses and cars use the same streets and lanes without any competitive advantages given for buses, meaning that they are always outperformed by cars. This can be improved in two ways, by improving the infrastructure for buses, or by improving the competitiveness of buses when using the existing shared infrastructure (Bradley and Kenworthy 2012).

> *"When buses operate on exclusive dedicated lanes, they tend to gain even more popularity by mimicking the speed advantages of metros, however, usually at a fraction of the construction cost." (Cervero 2013)*

The introduction of vehicles into the dedicated BRT lane, may decrease the probability of passengers switching to the BRT from other travel modes, e.g. from 65% to 46% (Mane et al. 2017).

BRT systems have differences in design, e.g. whether completely segregated bus lanes, station-like bus stops, ticketing systems on the platform, real-time information or signal priority along the entire corridor are implemented. There is no comprehensive evaluation on how these features influence travel behavior but they are assumed to be significant (Ingvardson & Nielsen, 2018).

The expectation of the regional master plan that the bus mode share will increase from 4% to 12% by 2040 thanks to Borgarlina implementation might not be met if it is not combined with strong policies aimed at making bus travel competitive to car travel. It can be achieved both through influencing relative travel times, e.g. through simultaneous closure of road traffic lanes, not funding construction of new car connections; and through influencing how bus travel is perceived, which would require strong BRT branding and improving the bus system's reputation.

Cycling infrastructure

Cycling was the primary urban transport mode until the 50s, but was quickly reduced to margin with the emergence of private cars (Gössling, 2013). Cycling has experienced a revival during the past decades in many places, but not without policy-support. Well-known bicycling cities of Amsterdam in the Netherlands, Copenhagen in Denmark and Münster in Germany have all seen rapid growth rates in cycling, up to it becoming the dominant travel mode with shares of close to 50% in all these cities (Gössling, 2013). This has not happened on its own, however, but instead through a process of a sequence of soft and strong policy measures (incentives and constraints) supporting the development.

Development of cycling infrastructure is one of the key factors boosting growth in cycling rates (Gössling, 2013). It inherently relates to the general competitiveness of cycling as a mode in comparison to cars, P.T., and walking, which Sick Nielsen et al. (2013) suggest as an important factor. The faster (and easier) it is to cycle, the more often the bicycle will be selected as the travel mode. Gössling (2013) found cycling infrastructure development as one key factor behind Copenhagen's success in making cycling as the dominant travel mode within the past couple of decades.

Public transportation image and fare prices

The overall image of public transportation effects increases people's intention of using it for their daily travel. The effect is however the strongest for trips to leisure activities, followed closely by trips to shopping centres, and the weakest for commuting purposes. In this same study however, subjective norms (whether people that are important to them support them using it or expect them to) did not significantly affect use intentions. (Zailania et al 2016). Price elasticities of transit are in the range of -.02 - -.05 in the first year and then increase to -0.6 - -0.9, and are stronger for leisure travel than commuting. However, quite a significant price drop is needed to persuade consistent car commuters to change to public transportation (Litman, 2004).

Even for city residents who already use public transportation, their perception of value, satisfaction and service quality affects their behavior intention on utilization, in other words their likelihood of continuing the use and recommending it to others. One study from Taiwan found significant positive coefficients between behavior intentions and their perceived value, service quality and satisfaction (Lai & Chen, 2011).

However, there are ways to improve public transport utilization without changing the transit infrastructure or pricing at all, which aim for voluntary travel behavior change. The approach includes informing people about the availability of existing travel options and services, and according to a study of Australia and the U.K. can increase the use of public transportation by 10-20%. The approach is reported to be a cost-effective way to reduce car dependency, and works best when there is already good transport infrastructure in place which is underutilized and has spare capacity. If the infrastructure is inadequate, it can backfire and lock in people's decisions to use cars, as they try out the services and consequently decide that it's not a good option for them (Stopher, 2005).

Lifestyles and mobility cultures

Travel behavior is shaped not only by urban structure, access to transportation infrastructure, and prices, but also by “soft” characteristics, such as attitudes, social norms, which can be aggregated to *mobility styles* (Anable, 2005, Ohnmacht et al, 2009; Prillwitz & Barr, 2011) and more broadly defined lifestyles. They are relevant for planning and policy making, as they influence the demand for travel modes and transportation infrastructure, and the acceptance for policy measures.

Together with the built environment, and urban-level transport policy, the travel-related attitudes form a complex socio-cultural setting which shapes mobility in a city-region. These configurations can be described as urban mobility cultures (Klinger et al., 2013; Klinger and Lanzendorf, 2016) which also include specific social conventions, habits, and discourses related to mobility. Urban form and transport infrastructure reflect cultural priorities of a city population, and in turn shape the “soft” variables by limiting or expanding possibilities or creating habits. Urban mobility cultures are dynamic, includes competing interests, and conflicts, and as such can change with time. However, they have high inertia and depend on long-lasting physical and cultural structures with a high level of path dependence. Mobility culture specific to Iceland and the Capital Region, such as high cultural and utilitarian importance of private cars (Colin-Lange & Benediktsson, 2011), and relatively low density and high car-orientation of the urban structure, are important factors which may slow down changes in travel behavior in the region.

According to Brand et al. (2019), incremental changes in efficiency and behaviour will not be enough to sufficiently reduce emissions and energy use in transportation systems. Transportation policies need to encourage change in lifestyles, that is, social norms and attitudes towards travel, cultural shifts from motorization to accessibility. Changing attitudes and norms, in turn, might influence policy through increased support for more radical policies (Brand et al., 2019). The need for cultural change and radical policies is especially true in locations where current mobility culture is centered around private cars, such as the Capital Region.

Car ownership rates

Increasing trends

The rate of car ownership has been quickly increasing in Iceland and the Capital Region (Statistics Iceland, 2020). It has also been the case in other countries, such as Great Britain (Geels, 2018), Finland, or Poland (Deloitte Poland, 2019).

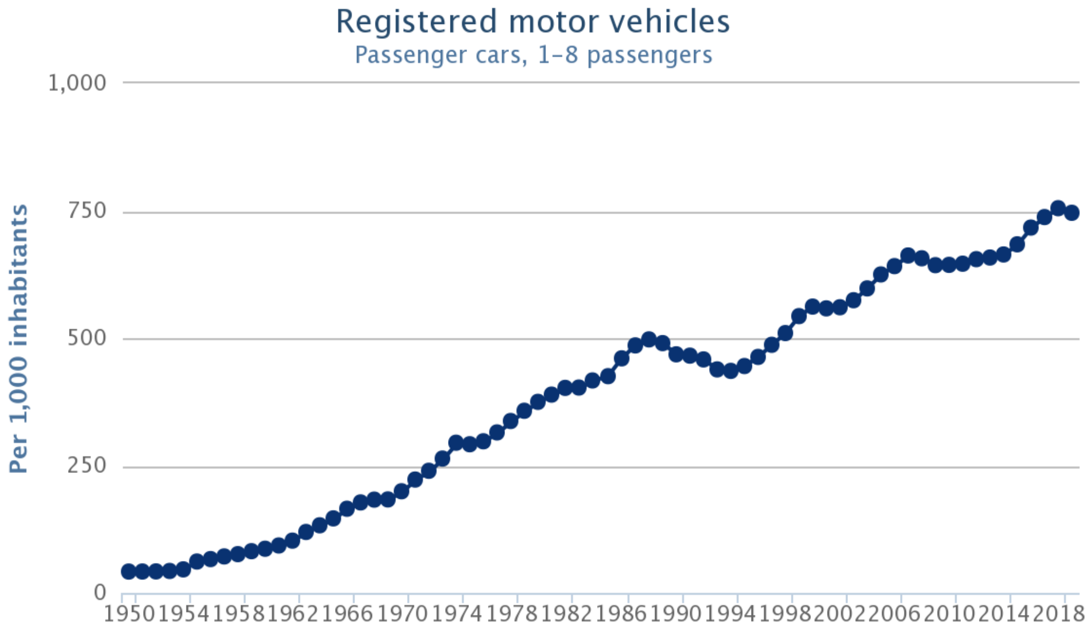


Figure 2: Changes in car ownership rate in Iceland since 1950 (Statistics Iceland)

The current car ownership rate is exceptionally high, with the number of cars reaching 70% of the population in the Capital Region, 13% up from 2000 (Reykjavikurborg 2020), and nearly 50% higher than the E.U. average. There are 1.84 private vehicles per household in the Capital Region. These numbers are similar to or higher than in auto-oriented cities in the U.S., such as Los Angeles, Phoenix, or San Diego. Infrastructure development has supported this change, showing, e.g., in the number of parking places going up at an even higher pace. As examples of pedestrian and transit-oriented cities, in Copenhagen, the cars per residents-ratio is less than one third, and Oslo is not far above.

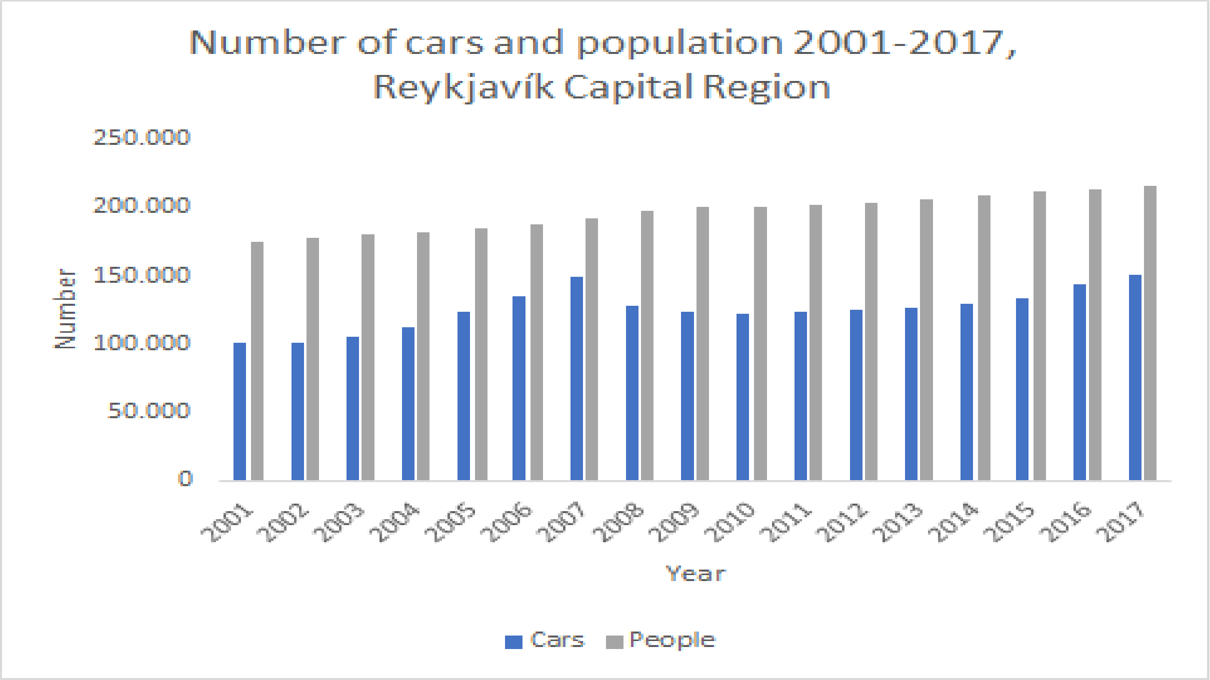


Figure 3: Changes in car ownership rate in the Capital Region since 2001.

General factors of car ownership increase

Some general factors have been found to predict changes in car ownership rates. Income has a substantial impact in low- and middle-income groups, but on higher income levels, the effect diminishes significantly (e.g., Kenworthy, 2018). Economic growth and rising incomes have very recently changed the travel cultures in developing countries like China (Jiang et al. 2017) and Mexico (Guerra 2015), but for example in the affluent Nordic countries for the majority of the population income is not a decisive factor anymore (Cao et al. 2019).

Many built environment characteristics have been found to affect car ownership levels, but findings are not unanimous, and the causal mechanisms can be very complex and difficult to reveal. However, car infrastructure seems to have a universal impact: more infrastructure means more cars using it (Kenworthy 2017). Similarly, better public transport service levels have been connected to lower car ownership rates (Cao et al. 2019; Zegras 2010), but with car infrastructure as an important confounding factor.

A typical decreasing trend in car ownership towards the city center has been detected in the Capital Region, similar to many other cities across the world (Ewing & Cervero 2010). However, although it is only in the immediate city center where the car ownership rate is significantly lower than elsewhere in the Capital Region, as shown in the Figure 4.

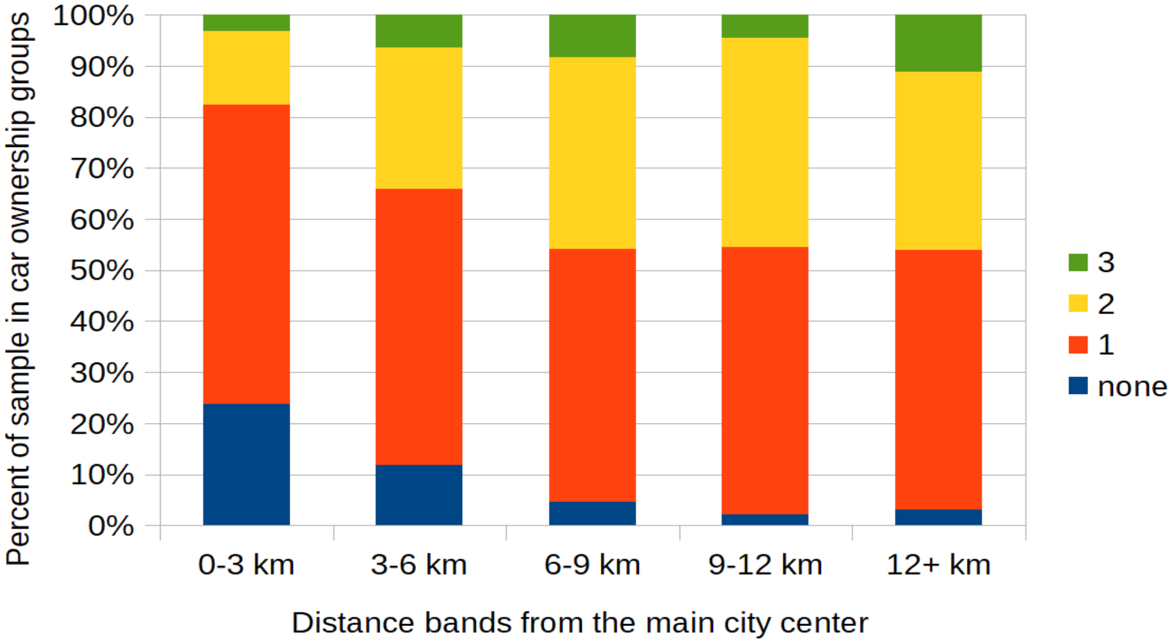


Figure 4: Car ownership in distance belts from the main city center in Reykjavik

Generally, higher density lowers car ownership, as in Reykjavik (see above), although, in many studies, the connection has remained relatively weak (Cao et al. 2019; Ewing & Cervero 2009). Increasing distance to the city center increases the probability of possessing vehicles (Cao et al. 2019). Still, it has been suggested that this impact is often overestimated due to the self-selection effect of those for some reason wanting to have and use cars residing in "car friendly" locations (Bhat & Guo 2007). Cao et al. (2019) found more green spaces to reduce car ownership and use. The magnitude of these impacts is not necessarily very high, as illustrated by Cao et al. (2019) for Oslo and Stavanger:

> *"if we could simultaneously double dwelling unit density, land use mix, four-way intersections per kilometre, and plaza density, we would expect a 10 per cent reduction in VKT."*

Even though Messenger and Ewing (1996) suggest that density affects the mode of travel only through car ownership, newer studies (e.g., Czepkiewicz et al. 2019) show that the picture is more nuanced. Multimodal households and individuals who possess cars but do not use them regularly or use them only to some destinations (typically for commuting) are relatively common.

Point of saturation

There might be some level of car ownership rates, which is a saturation point, after which it no longer increases. It has also been suggested that this relates instead to infrastructure capacity than to some kind of maximum level of auto-ownership (Kenworthy 2017). However, there likely also is a limit to how many cars people are willing to possess. Still, evidence from cross-comparisons of global cities indicates that infrastructure might limit car ownership to a level much below the "personal motorization saturation point" (Kenworthy 2017). When car infrastructure capacity runs out, and other modes than private car become competitive in travel time, the incentive to possess more vehicles is significantly reduced. Those designing the urban structure thus have an essential role to play in steering a specific community towards the auto, transit, or active transport orientation. Decreasing trends: do we see "Peak Car" or the beginning of post-car society?

In some places, car ownership and use decreased after 2007, which gave rise to speculations about "Peak Car" or post-car societies (Newman et al., 2013). According to Geels (2018, p. 91), these may have been premature, since most probably the decrease "may have been a temporary response to high oil prices and the financial-economic crisis rather than a long-term structural trend." Kenworthy (2017) suggests that the "Peak Car" phenomenon is happening, but has to do with several factors. One important is the car infrastructure in terms of either inducing more cars and more driving, or decline of car ownership and driving. If other modes become more competitive and appealing, e.g. in terms of travel speed, car ownership will decline.

There are also some indications of cultural changes related to car ownership. It is increasingly less common among younger generations to treat the car as a symbol of status, and they often arrange their lives so that they do not need to possess vehicles (Newman et al. 2013). Concerns over environmental and health issues related to mobility (air quality, climate change, impact on pedestrians and neighborhood quality), are gradually becoming more common, and they are to some extent related to car ownership and use. Preferences for living car-less lifestyles in walkable and centrally located neighborhoods are more common among the younger than, the older generations (Brown & Vergragt, 2016). Nowadays, people are entering life course stages associated with car ownership – such as having children, having a stable job, and in general having a way of life focused around family and home - later than older generations did. Furthermore, younger generations more often choose not to have children at all (e.g. Clark et al. 2016). Finally, millennials are thought to be less concentrated on owning and more willing to rent or share (Brown & Vergragt, 2016), which has been linked to the increasing popularity of "micromobility", e.g., e-scooters, among young people. Still, these changes and trends may not penetrate the whole cohort, but just some percentage of people who comprise "the generation", and these developments are not universal.

Many large American cities have recently seen both a growth in car ownership per population and a growth in percentage of car-free or car-light households (with fewer cars than workers). Seattle has seen the fastest growth in the proportion of car-free and car-light households. The rise in car-ownership is mostly due to an increase in the percentage of households with 2 or more vehicles and, to a lesser extent, an increase of car-light households (Schaller, 2019).

Mobility as a Service (MaaS)

Mobility as a Service (MaaS) is a concept that has only just started to emerge within the current gig-economy and encompasses bike-sharing, car-sharing, pop up bus, ride-sharing, and self-driving car services. As a rather new technology with many applications and ramifications, there is limited research on MaaS services. The Nordic Council of Ministers thus published research on MaaS transportation systems in a Nordic context. Within this study it was estimated that as MaaS modal shares increase, a decrease in road traffic and vehicle ownership levels could be expected according to the level of MaaS modal shares. This study estimates that MaaS can reduce VKT by 10-35% and the integration of MaaS has the potential to decrease CO2e emissions between 0.2-10% from the baseline scenario for Nordic transportation systems (Laine, et al, 2018).

This research gave little insight however in how many MaaS vehicles would be required to service the transportation demand from the growing MaaS modal share. Data was therefore taken from New York City, a more saturated market in terms of ride-sharing, to determine the number of vehicles required to service the demand from MaaS users, published by New York City's Taxi and Limousine Commission. This data included the number of monthly rides taken by users and the number of vehicles dispatched to service these users, giving an indication of the number of MaaS vehicles that would be required to service the MaaS share of daily travel demand (Taxi and Limousine Commission, 2020).

Electric vehicles

Electric car deployment has been growing rapidly over the past ten years, with the global stock of electric passenger cars passing 5 million in 2018, an increase of 63% from the previous year. Around 45% of electric cars on the road in 2018 were in China (a total of 2.3 million). In comparison, Europe accounted for 24% of the global fleet, and the United States 22% (IEA, 2019a).

In the Nordic region, the stock of electric cars has been expanding steadily since 2010.1 It reached almost 250 000 cars by the end of 2017 and accounted for roughly 8% of the global total of EVs in 2016. The Nordic region has one of the highest ratios of electric cars per capita in the world (IEA, 2018). Four of the five Nordic countries have a market share above 2%, and all are experiencing a progression of PHEV market shares.

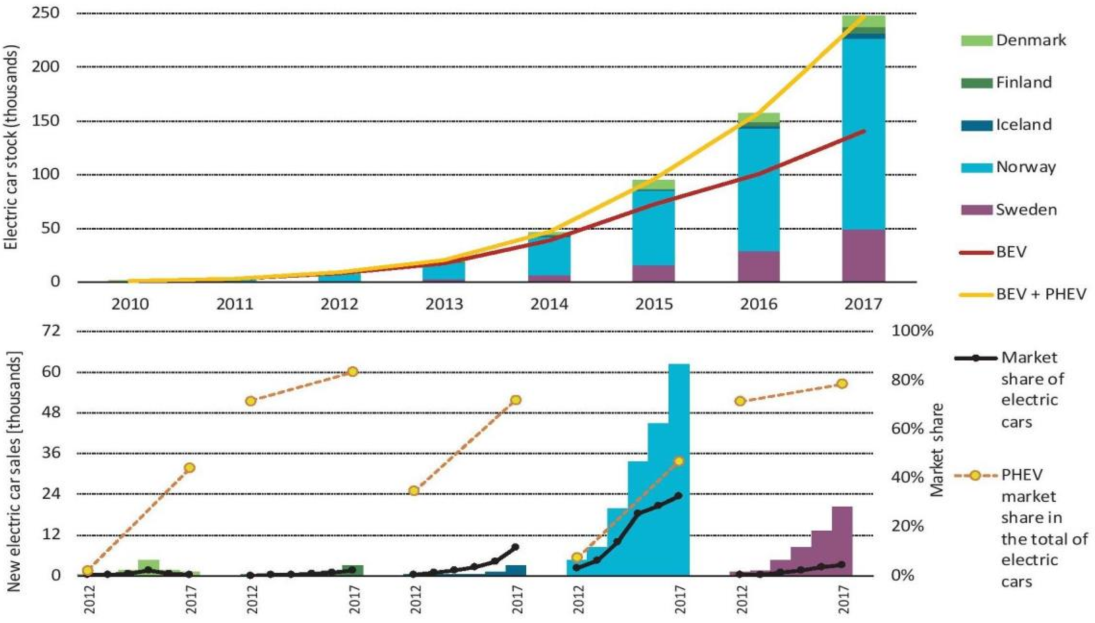


Figure 5: Number of electric cars, new sales and market share in Nordic countries, 2010-2017 - source: IEA, (2018)

The policy ambition of the Nordic region – demonstrated by commitments to decarbonize the energy system, targets for E.V. deployment and specific announcements on the continuation or the strengthening of related policy measures over the next few years – suggest that the electric car fleet in Nordic countries will grow significantly. By 2030, it is projected that 4 million electric cars will be on the road in the region, implying more than a 15-fold growth of the electric car stock from 2017 volumes (IEA, 2018).

Policies and Regulations

Policies have major influences on the development of electric mobility. Policy approaches to promote the deployment of E.V.s typically start with a vision statement and a set of targets. An initial step is the adoption of electric vehicles and charging standards. Economic incentives and regulatory measures are often coupled with other policies that increase the value proposition of E.V.s. Such policies often aim to harness the multiple co-benefits arising from greater electrification of transport, most prominently energy diversification in a sector that is 90% dependent on oil products and the reduction of local pollutant and GHG emissions. Measures that provide crucial incentives to scale up the availability of vehicles with low and zero tailpipe emissions include fuel economy standards, zero-emission vehicle mandates and the rise in the ambition of public procurement programmes (IEA, 2018).

Several studies have focused on the implications of fuel prices, vehicle taxes, future price of E.V.s, recharging concerns as well as fiscal policies on the market share of E.V.s in Iceland (Fazeli, et al., 2017, Shafiei et al., (2012), Shafiei et al., (2018), Shafiei et al., (2019)).

Shafiei et al., (2012), developed an agent-based model to study the market share evolution of passenger vehicles in Iceland until 2030, considering the impacts of fuel prices, vehicle taxes, future price of E.V.s and recharging concerns. The results show that E.V.s would seize the market completely in the scenario combined of high gasoline price, decreasing E.V. price without tax and no worry about the recharging of EVs. The successful penetration of EVs in the scenarios with low gasoline price and combination of medium gasoline price and constant EV price needs policy support like tax exemption.

Thus, Shafiei et al., (2018) focused on the Macroeconomic effects of fiscal incentives to promote electric vehicles in Iceland on government tax revenues/expenditure and consumer car ownership costs. The fiscal policies, which are applied to both vehicle usage patterns and upfront purchase cost, include petroleum fuel tax levies, vehicle tax exemption, extra fees and subsidies. The results indicate that vehicle upfront fiscal incentive is the most effective strategy to promote the market penetration of E.V.s.

Then, the implication of a new tax reform proposal by the Icelandic government and of a banning condition in which the new purchase of ICEs and HEVs (with petrol or diesel fuels) will not be permitted from 2030 onward, have been studied. Shafiei et al., (2019) applied an analytical tool that includes a techno-economic simulation model of the integrated energy transport system which is linked to an Icelandic macroeconomic general equilibrium model. The results show that although the tax-induced technological solution aimed at encouraging the adoption of E.V.s will enable a deep GHG emissions reduction in the long term, it will not be enough to meet the short-term climate targets.

To provide decision support to policy makers, Fazeli, et. al (2017) developed an evaluation framework of fiscal policies for the adoption of electric vehicles by linking Multi-criteria decision analysis to the energy systems model. Five fiscal policy incentives were compared in terms of government revenue, consumer's vehicle ownership cost, the GHG mitigation potential and energy security. Then, the policy scenarios are compared using the TOPSIS method. According to the estimated performance indexes for policy scenarios, Feebate+Tax scenario receives the highest rank. In the Feebate+Tax scenario, a fee equivalent to 20% of conventional ICEV price is imposed on both petroleum ICEVs and HEVs, while an equivalent rebate value is provided to the purchase price of light-duty BEV and heavy-duty PHEV. In addition, an extra excise duty and a carbon tax are levied on petroleum fuels.

Fuel Economy

Another key factor to reduce the GHG emissions from the transport sector is to increase the fuel economy of vehicles. However, while the average fuel economy of vehicles continues to improve, the rate of progress has slowed in recent years (IEA, 2019b). Average fuel consumption of light-duty vehicles (LDVs) improved by only 0.7% in 2017 slowing from the 2005-16 rate of 1.8% per year. To get on track with the SDS, which is aligned with the Global Fuel Economy Initiative (GFEI) 2030 targets, an annual improvement of 3.7% is needed (IEA, 2019c). Meanwhile, the competitiveness of E.V. is heavily dependent on battery cost and technology improvements. It's expected that battery costs will drop by 19% per cumulative doubling of manufactured capacity and the average battery energy density will double by 2030 to more than 200 Wh/kg. The effects of these technological advancements are twofold: smaller battery capacity requirements – up to 15% by 2030 – and lower vehicle weight (Soulopoulos, 2017).

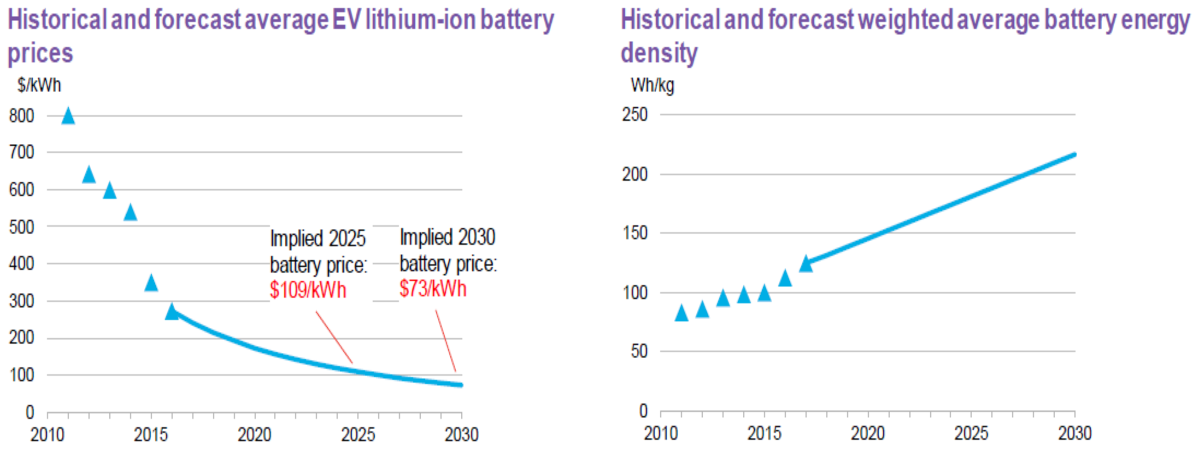
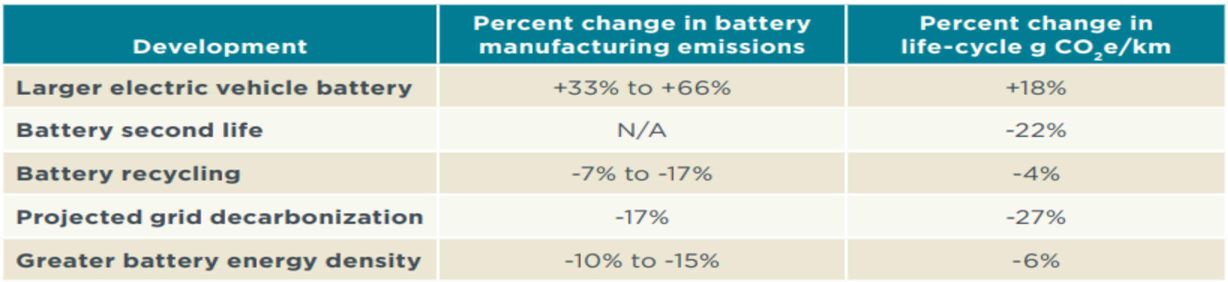


Figure 6: Historical and Projection of Battery Costs and technological development of battery energy density (Soulopoulos, 2017)

Impacts and future changes of impacts of E.V. battery production

Within the discussion surrounding electric vehicles, a focus is often placed on the environmental impacts associated with E.V. battery production. With good reason, as the production of the battery packs for E.V.s have a high resource requirement and are emission intensive to produce. According to research performed by the IVL Swedish Environmental Research Institute (2017), the GHG emissions associated with battery production is variable but with a clear connection of increased GHG emissions associated with larger battery packs (in terms of capacity in kWh). To model the potential impact of technological changes, research from the International Council of Clean Transportation (ICCT) was used, outlining the effects of battery manufacturing on effects of battery manufacturing on E.V. life cycle GHG emissions. This research estimated that GHG emissions associated with manufacturing battery packs can be impacted by larger batteries being produced (to meet the higher vehicle range demands), battery recycling, projected grid decarbonization, the need for battery replacement, and greater battery energy density. These Potential reductions in greenhouse gas emissions resulting from improvements in battery manufacturing and use by 2030 are estimated by (International Council of Clean Transportation, 2018).

Table 1: Potential reductions in greenhouse gas emissions resulting from improvements in battery manufacturing and use by 2030 (International Council of Clean Transportation, 2018).



Development	Percent change in battery manufacturing emissions	Percent change in life-cycle g CO_2e/km
Larger electric vehicle battery	+33% to +66%	+18%
Battery second life	N/A	-22%
Battery recycling	-7% to -17%	-4%
Projected grid decarbonization	-17%	-27%
Greater battery energy density	-10% to -15%	-6%

This results in a minimum and maximum range of change to GHG emissions associated with battery pack manufacturing to be -16% and 32%, respectively by 2030. Using a review of 20+ EV LCA studies, the authors of this study applied these potential changes to the estimated life cycle emissions of E.V. battery and vehicle production to model the potential changes in the GHG intensity of E.V. vehicle production.

Materials and methods

Developing future scenarios

We have developed seven scenarios of future changes in the transportation system of Reykjavik Capital Region. We first developed the scenarios qualitatively by writing plausible storylines. In the development of storylines we used a socio-technical approach (Geels et al. 2017) with consideration of both technological and socio-cultural developments (Anable et al. 2012, Brand et al. 2019). Each of the scenarios is primarily defined by three layers: 1) Macro-scale developments that describe the international and national context which influences incomes and socio-demographics, and major shifts in political orientations, technologies, and cultures, 2) Technological developments that entail a shift to electric powertrain, more efficient engines and new mobility solutions (such as Mobility as a service (MaaS)), and policies that support or hinder adoption of the advanced more efficient technologies, 3) Lifestyles, social norms, attitudes, consumer preferences, and travel behavior patterns.

The scenarios were developed based on policy documents in the region and academic literature that describes main factors of change and policy instruments that influence travel behavior. In developing the scenarios, we focused on four main components:

1. Urban structure, including densification (close to the city center and in transit corridors), monocentric vs polycentric urban forms, access to public transportation, cycling infrastructure, pedestrianization.
2. Technologies, including the battery cost of EVs, fuel economy, Mobility-as-a-Service (bike-sharing services, car-sharing services, pop up bus services, self-driving car services), reductions in the production-phase GHGs from EVs (or combustion engine vehicles)
3. Policies and regulations, such as parking restrictions, creating car-free zones, free public-transit tickets for commuters, Increase of infrastructure stock, for both roads and public transport, banning of ICEs, VAT exemption for light and heavy BEVs
4. Lifestyles, including vehicle purchase preferences, load factor of cars and buses, travel mode preferences, public transportation image, the car as a symbol of status, driver licence penetration, car ownership, localization of lifestyles (e.g. local living), public support and activism in favor of decarbonization policies, telework, health and well-being concerns related to mobility, and public discourses.

These four components together define how the future turns out to be regarding the climate impact of the passenger transport sector. Partially the development can be influenced by a certain city, but global trends can also overrule any local steering. Thus, regardless of how strongly a city acts to push forward de-carbonization of the transport sector, long-term outcome is highly uncertain and the range in the level of emissions at a certain point in time in the future wide. In this study the aim is to define the main drivers of the future emissions from the passenger transport sector in Reykjavik Capital Region in Iceland, and assess the potential outcomes of different development pathways.

Modeling

To estimate the associated direct and indirect GHG emissions for the scenarios described above, both the direct emissions from the passenger car fleet, busses, and the transport service industry (taxis, MaaS such as Uber, etc.) as well as the indirect emissions associated with the production and end of life of passenger vehicles and busses were calculated. The passenger vehicle fleet was disaggregated by BEVs, PHEVs, HEVs, diesel, and petrol vehicles. The bus fleet was disaggregated by diesel busses and BEV busses.

Direct GHG Emission Modelling

Exactly calculating the direct emissions from a city's transportation sector is a near impossible task, and instead, to get an estimate of the transportation sector requires the development of a model. Modelling direct GHG emissions from the transport sector is part travel behavior analysis, estimating how much travel demand exists per citizen per day, mode share, and utility factors. It is additionally part technological modelling, determining the transition rate at which busses and passenger vehicles will be electrified and the emission factors of different powertrain types for both passenger vehicles and busses.

Behavioral model

To establish an initial state of the travel behavior of Reykjavik's citizens for further modeling, a 2017 travel survey by Gallup was used. This survey asked respondents to record their travel activities during a specified day. The respondents were asked to record the purpose of their activity (i.e. go to work, shopping, return home, etc.), the time of departure and time of arrival to the destination, as well as the travel mode used (i.e. car, bus, bike, etc.) to commute to their destinations. This survey had 23,666 travel activities, with an origin and destination for each activity, from a total of 6,059 respondents (Gallup, 2017).

The data collected through the survey was used to determine the initial value for total travel demand, mode share, and average distance traveled according to mode share taken. Besides, the average daily travel distance was estimated to be 26.17 km per capita per day. The mode share by distance can be seen in Figure 7. Passenger vehicles were assumed to service 86.2% of all travel demand, busses 4.4%, and taxis/transport services 0.2%, which leads to an estimated vehicle kilometer travel (VKT) demand of 23.74 km per day.

To predict future changes in travel demand and mode shares we relied on literature sources. To specify expected changes in travel behavior in S1a and S1b scenarios, we used predictions included in strategic and planning documents in the Capital Region (SSH, 2015). To predict changes in other scenarios, we used elasticities that describe how travel behavior variables change with changes in background variables, such as urban structure and transit provision based on multi-city analyses (e.g. McIntosh et a., 2014); current and recent statistical data that describe travel behavior in cities comparable to Reykjavik; statistical data on historic changes in travel behavior in different cities that occurred after specific urban developments, such as introduction of bus rapid transit (BRT) system (e.g. Ingvardson & Nielsen, 2018), or introduction of cycling policies (e.g. Civitas 2016, Pucher et al. 2011); predictions on future changes in travel behavior in different cities and countries (e.g. Brand et al. 2019, Creutzig et al. 2012, Fearnley 2013, Cats 2016, Hess 2017).

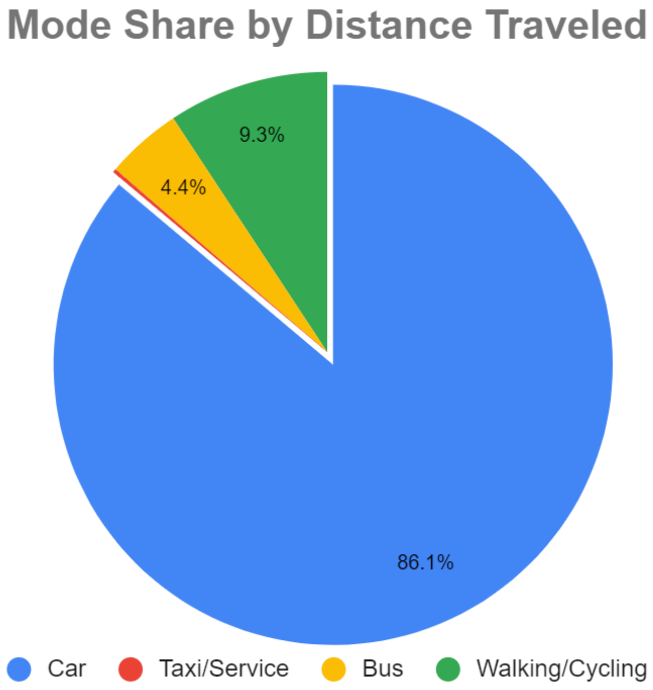


Figure 7: Mode share by distance

Estimating a utility factor is additionally important when modelling travel behavior. The utility factor of a passenger vehicle, bus, or transport service determines the average number of people being serviced by a vehicle. The more people being transported by a vehicle, the less emissions. The utility factor for passenger vehicles was estimated to be 1.195 persons per vehicle, derived through the use of the Gallup travel survey, in which respondents reported whether they were a passenger of a vehicle or the driver. The utility factor for busses was estimated to be 23.44 persons per kilometer travelled by bus, using the Gallup travel survey as well as numbers reported by the local public transport company, Strætó. The utility factor was calculated by using the total passengers and kilometers traveled by busses in the Strætó report, and then using the average distance traveled per bus trip within the Gallup survey to determine the average number of passengers per kilometer traveled by a bus (Strætó, 2018).

To scale the model to Reykjavik's population, the city's population estimate was taken from The City of Reykjavik's databases for the metropolitan area of Reykjavik (City of Reykjavik, 2020). The most recent reported population count was 222,484, and following recent years' average population increase, 2019's population was estimated to be 224,709. An estimated annual population increase of 1.1% was assumed for all scenarios within the study, in line with Reykjavik city planning estimates (SSH, 2015) as shown in Figure 8.

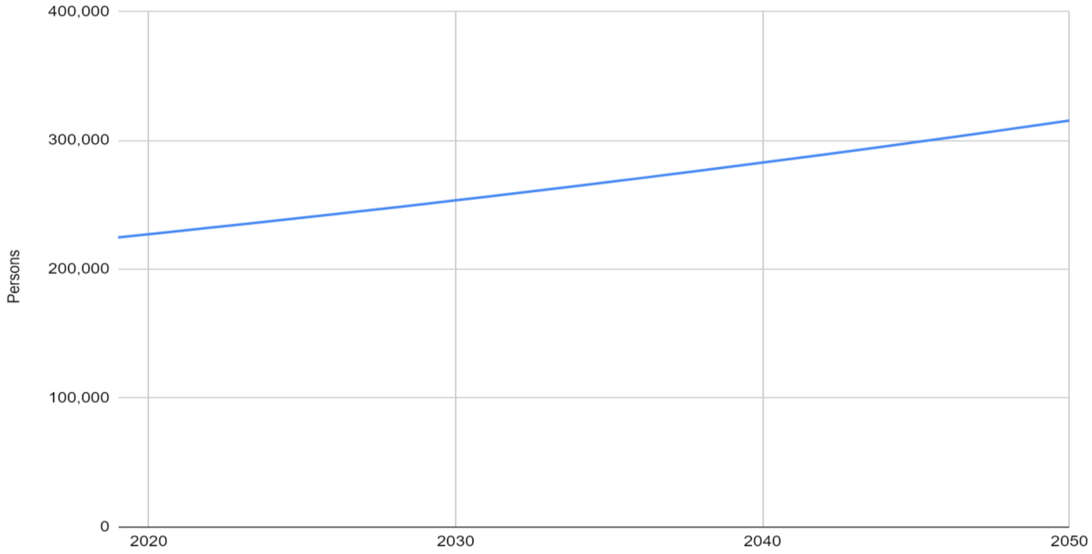


Figure 8: Projected Reykjavik metropolitan area population 2019-2050 (Reykjavíkurborg, 2018.)

Technological model

The energy system model for Iceland (UniSyD_IS) is applied to simulate the implications of transport fiscal policies on passenger vehicle fleet electrification during 2015-2050. UniSyD_IS is a partial-equilibrium system-dynamics model with a detailed representation of energy resources, conversion technologies, fuel infrastructure, and vehicle fleets. It is capable of endogenously simulating the vehicle fleet evolution using sector modelling of fuel supply, energy markets, refueling/recharging infrastructure, and fuel demand.

The model has been tested with applications in different case studies and it has been applied to the New Zealand economy (Shafiei et al. 2017) and the Iceland energy systems (Shafiei, et al. 2019). The model includes four main sub-sectors (Shafiei, et al. 2018).

1. Energy supply: This sector estimates the amount of fuels that can be supplied at various market prices and production costs. It incorporates four key components involving resource supply curves, existing plant capacities, planned or future capacities, and production costs.

2. Refueling/recharging infrastructure: This sector determines the refueling station service availability as an important factor that changes consumer preferences towards AFVs. Station profitability is used to represent fuel station viability.

3. Fuel demand: A vehicle choice algorithm forecasts the market share evolution of different vehicles within LDV and HDV fleets. A multinomial logit (MNL) framework gives the probability that consumers adopt new vehicles based on their preferences toward vehicles' attributes. Vehicle attributes included in the consumer utility function are vehicle purchase price ($), annual maintenance cost ($/year), fuel cost per kilometer ($/km), battery replacement cost for electric vehicles ($), vehicle driving range (km), and refueling service availability (relative to conventional petroleum infrastructures).

4. Energy markets: This sector attempts to balance the demand with the supply curves of production plants by changing price signals. The algorithm is based on a market-oriented

economic system in which fuel supply viability is determined by market clearing price and supply profitability (Shafiei et al., 2015a). In the short term, energy price signals are transferred to corresponding production plants to determine the amount of fuel supply. In the long-term, the forecasted fuel prices play a crucial role in installation of new capacities. For a detailed description of the algorithm see (Shafiei et al., 2015b).

Technological development is considered as a major driver to decarbonize passenger transportation. Therefore, the UniSyD_IS model was utilized to assess the impacts of a set of policies aimed at facilitating the transition to electro-mobility and improve the efficiency of the vehicle fleet compared to the current fuel and vehicle tax scheme. The supportive policies include the new tax reform proposal on fuels and vehicles (Ministry of Finance and Economic Affairs, 2018), ban on new sales of ICE and HEV from 2025 and an improvement of 15% in the efficiency of new vehicles (Soulopoulos, 2017).

The outputs of the UniSyD_IS model included the composition of the passenger vehicle fleet and the estimated Tank-to-Wheel (TTW) or direct emissions coming from each vehicle type. The fleet composition and emission factors per vehicle type can be found in the appendix. These composition and emissions factors were assumed to be the same for both the passenger vehicle fleet as for the transportation services fleet.

Indirect GHG Emission Modelling

The indirect emissions from the transport sector incorporated into this analysis originate from the GHG emissions associated with production and disposal of the different vehicle types considered within this analysis. To determine the annual number of vehicles being purchased and disposed, historical fleet data was used.

Life Cycle Emissions

To estimate the GHG emissions associated with producing and disposing a specific passenger vehicle type, a literature review of LCAs was performed. Within this literature review, 20+ published studies were reviewed, providing the following average production and End-of-Life GHG emissions for the associated vehicle type:

Table 2: Production and End-of-Life emissions per vehicle type (t CO2 eq.)

	Production Emissions	End-of-Life Emissions
ICEV (Petrol and Diesel)	6.22	0.21
PHEV (and HEV)	9.56	0.24
BEV	11.30	0.27

The production and EOL emissions for busses were taken from a study performed by Sánchez et al. From this research, it was estimated that the production and EOL emissions per bus type were as follows (Sánchez et al, 2013):

Table 3: Production and End-of-Life emissions per bus type (t CO2 eq.)

	Production Emissions	End-of-Life Emissions
Diesel Bus	57.2	7.3
BEV Bus	79.5	9

Vehicle fleet size and annual purchases and disposals

In order to determine how many vehicles were being purchased or disposed annually, historical fleet data was used. It was estimated that in 2019, Reykjavik's passenger vehicle fleet was 158,965 vehicles, extrapolating from data published by the City of Reykjavik (Reykjavíkurborg, 2017). The 2019 number of busses was extrapolated from Straeto's annual report, where it was assumed that Straeto was operating with 98 busses in 2019 (Straeto, 2019). The only transportation services legally allowed by the country are taxi services, in which every taxi needs to be licensed. Through personal communication with the Icelandic Transport Authority, it was determined that as of 2019 there were 558 taxi licences in Reykjavik (Icelandic Transportation Authority, 2020).

From the literature review performed, the average lifetime of a passenger vehicle was estimated to be 195,000 kilometers. Assuming that an average Icelander drives 15.000 km per year, the average lifetime of a car was estimated to be 13 years (Icelandic Automobile Association, 2018). Therefore, to determine the number of cars disposed of in a specific year, 1/13th of the passenger vehicle fleet size from 13 years previous was assumed to be disposed of. The vehicle type composition of the vehicles disposed was determined by the assumed vehicle fleet composition during the associated historical year's vehicle fleet.

Through the determination of the quantity of each vehicle type being disposed of during a specific year, and an estimation of the size and composition of that year's vehicle fleet, the estimated number of vehicles purchased by vehicle type could be determined. This same methodology was applied for busses and the transportation service fleet. Using the number of purchases and disposals of each vehicle type and GHG emissions associated with each of these processes, the indirect emissions associated with car fleet turnover could be calculated.

Estimating GHG emissions

Direct GHG emissions

The direct emissions associated with the transportation sector are related to the TTW emissions coming from each vehicle. In order to calculate the total GHG emissions, the inputs from the behavioural model section were used to model Reykjavik's travel behaviour in order to get an estimate of the total direct GHG emissions associated with the amount of transport activity required to meet Reykjavik's travel demand.

The direct emissions were calculated using the follow formula, adapted from previous research (Setiawan et al., 2019):

$$Annual\ Direct\ GHG\ emissions\ =\ AD\ *\ MSi\ *\ \ UFi\ \ *\ VTi,j\ \ *\ \ EMFi,j$$

Where *AD* is the estimated travel activity demand and MS is the modal share by distance of modal choice i, where i represents travel by passenger vehicle, bus, service, or personal transportation such as walking or cycling. Each modal choice has an estimated *UF* utility factor which determines the average amount of passengers a modal choice can service. Each modal choice was then broken up by *VT* vehicle type *j*. For passenger vehicles, this study assumed 7 vehicle types: ICEV petrol, HEV petrol, PHEV petrol, ICEV diesel, HEV diesel, PHEV diesel, and BEV. For busses only diesel and BEV busses were considered to be within the scope of this study. Each vehicle type, for both bus and passenger vehicles, had an *EMF* estimated emission factor associated with it, measured in grams CO2 eq per kilometer. These emission factors for each scenario can be found in the appendix.

Indirect GHG emissions

The indirect emissions are associated with the life cycle emissions due to the production and disposal of each vehicle. The GHG emissions associated with each of these processes for each vehicle type can be seen in the previous section along with the methodology for determining the number of vehicles purchased and disposed of in a specific year. With these values, the annual indirect GHG emission can be estimated using the following formula:

$$Annual\ Indirect\ GHG\ emissions\ =\sum_{j} Pj\ *\ \ PEj\ \ *\ \ Dj\ \ *\ \ EOLj$$

Where *P* represents the number of vehicles of type *j* purchased that year, multiplied by the *PE* production emissions associated with that vehicle type. Summed with the number of vehicles of type *j D* disposed of in the same year, multiplied by the emissions associated with a vehicle of type j's *EOL* End-of-Life, this results in the annual indirect GHG emissions associated with a vehicle fleet's turnover.

Decarbonization scenarios

This section includes a description of storylines behind each scenario and assumed changes in variables that influence emission levels from transportation. The resulting scenarios are most generally described as:

- **S1. Business-as-usual (BAU)**, used as a reference scenario, following the targets set by the cities in the region and the regional administration, in two variants:
  - **S1a. BAU without changes in travel behavior**, based on conservative assumptions of the regional master plan, where projects described in the plan are realized, but travel behavior does not change or changes minimally.
  - **S1b. BAU with changes in travel behavior**, based on more optimistic predictions of the regional master plan, where projects described in the plan are realized and results in changes in travel behavior.
- **S2. Urban structural change (USC)**: includes strong focus on land-use and transportation plans and policies aimed at public transportation improvement, transit-oriented development, densification, and improving conditions for walking and cycling, without significant changes in lifestyles.
- **S3. Urban structural change + Lifestyle change (USC+LS):** refers to the situation that the strong focus on land-use and transportation plans (public transportation improvement, transit-oriented development, densification, and improving conditions for walking and cycling), combined with strong demand-side policies (to reduce the use of private car) resulted in significant changes in lifestyles.
- **S4. Technological change (Tech):** with strong policies aimed at transport electrification (rapid adoption of EVs and electric buses) and digitized mobility solutions (mobility as a service, MaaS), that have a notable potential to reduce both emissions and kilometers travelled by private cars
- **S5. Integrated Approach (IA):** The world and the region grasp the problem of climate change, act accordingly, and changes in both technologies and lifestyles combine and together bring significant decarbonization effects.
- **S6. Worst case (WC)**: the-warmer-the-better, presuming macro-scale developments pushing global and regional politics away from decarbonization targets, with weak or no development towards GHG reductions in any aspect, globally or locally.
- **S7. Radical Change (RC):** describes a state that climate change become an imminent threat and countries must take the responsibility for the emissions occurring within their national boundaries, as well as for the indirect emissions occurring due to the use of imported goods and services. At the urban level, there will be strong restrictions to private car use, fiscal disincentives to possessing and operating vehicles, and strong support for MaaS, public transport and active modes of travel.

Figure 9 illustrates the scenarios considering the changes in four key components of urban density, public transport and active travel oriented lifestyle and technology development.

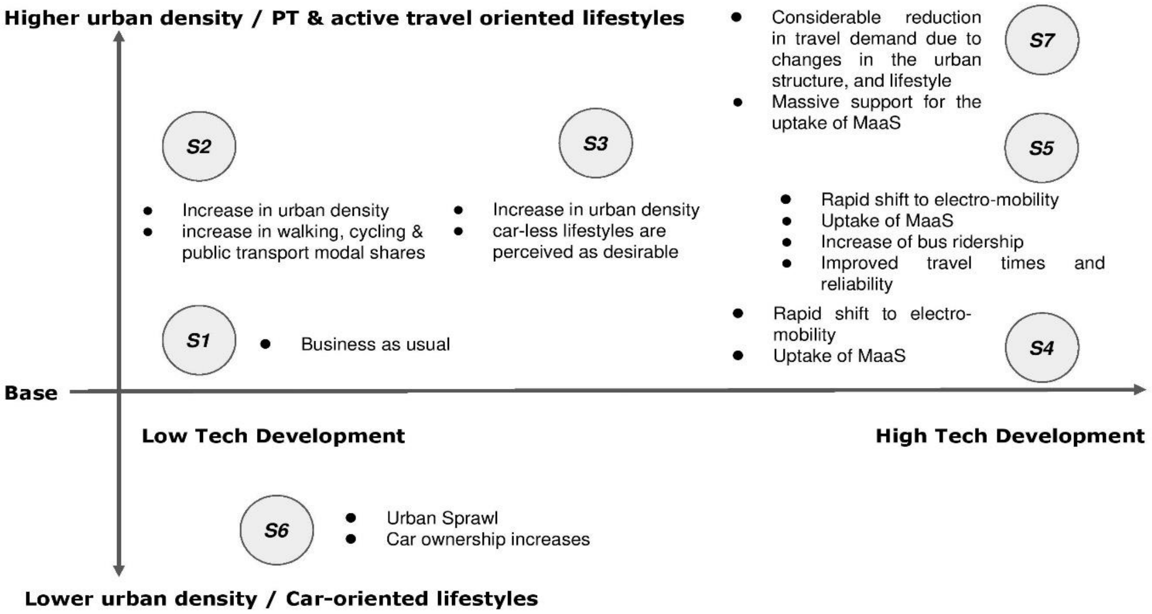


Figure 9: A general description of the scenarios, their differences and similarities

S1: Business as Usual

The scenario is based on policies outlined in strategic documents in the Capital Region and consists of two sub-scenarios that mirror predictions presented in the documents: **S1a**, in which the projects outlined in the strategies (e.g., Borgarlína) are implemented but result in only very moderate change, and **S1b**, in which implementation of the projects leads to change of travel behaviors (mostly an increase in public transportation use and a decrease in car use).

Macro-scale developments

The scenario does not involve any major changes on a macro-scale. There is a slow and gradual increase of the emphasis on reducing emissions, following current trends. This is reflected in policies at various levels but these are not very radical, and there is only some change in lifestyles and social norms towards environmental concerns and less consumption. There are some state interventions towards decarbonization in transportation and other sectors. Subsequent elections lead to governments that follow current policies but with differing strength and success.

Changes in urban structure and transportation system

Borgarlína is fully developed by 2033, according to the plan. Urban densification is mostly concentrated around Borgarlína stations, and there is much less densification of the urban area close to the city center. The domestic airport area is not developed. As outlined in the regional master plan, by 2025, 10% of people live in the city center, 2% in Smaralind center, 8% in other centers, 25% in transit-oriented zones, and 53% in other parts of the city. By 2040, 66% of residents lives in places where PT access is good, in centres and transit-oriented zones: 10% in Miðbær (up from 9%), 2% Smáralind and Mjódd (as it is now), 9% in other centers (up from 6%), and 45% in transit-oriented zones (up from 14%). Travel times decrease in Borgarlína corridors and reliability of bus travel is improved, which leads to a moderate modal shift from cars in scenario S1a, and a stronger modal shift in S1b. In the S1b scenario, there is an improvement in bus system reputation which supports changes in modal share. At the same time, car infrastructure is continuing to be developed, as outlined in the plan, and there are no major restrictions or disincentives regarding car ownership and use, which slows down further changes in travel behavior.

Changes in travel behavior and vehicle fleet

There is some progress in changing travel behavior. Thanks to urban densification and better PT provision, the average travel demand per person moderately decreases to 25.44 km/day by 2050 in both S1a and S1b. In S1a, only a moderate increase in PT mode share is observed (6% by 2030, 8% by 2040, and 10% by 2050). In S1b, PT mode share reaches 10% by 2030, 12% by 2040, and 14% by 2050. In both scenarios, mode share of cycling and walking combined stays at the 2019 level, around 9.3%. Private care mode share drops to 75.7% by 2050 in S1a, and to 61.2% by 2050 in S1b, thanks to the increase in PT and MaaS/AV mode shares. The adoption of AVs and MaaS is relatively slow and only reaches 5% in 2050.

In both S1a and S1b scenarios, car ownership does not change compared to the 2019 level and stays at 707 cars per 1000 people. With an increase of population, that means an increase of the fleet by about 20 thousand new cars every 10 years. At first, the adoption of electric vehicles follows the recent trend. By 2030, the registration of new ICEVs is banned and the adoption of EVs speeds up thanks to that. Battery electric passenger vehicles (BEV) comprise 16.7% of the fleet by 2030, 29.9% by 2040 and 40.6% by 2050. Hybrid and plug-in hybrid electric vehicles (HEV and PHEV) comprise 33% of the fleet by 2030, 39.6% by 2040 and 40.3% by 2050. There have been no diesel buses operating since 2032. By 2050, 98.75% of the buses are electric and 1.25% methane. The bus fleet is expanded according to the expansion of the BRT system to reach 160 buses by 2050.

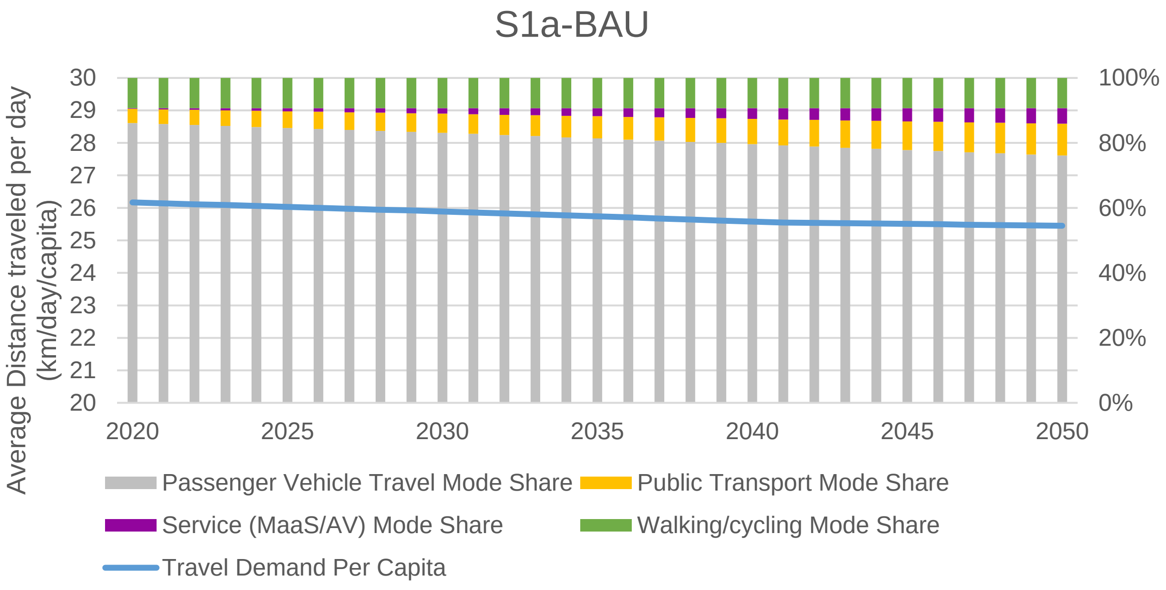


Figure 10: Changes in travel behavior variables in scenario S1a: business as usual without behavioral change.

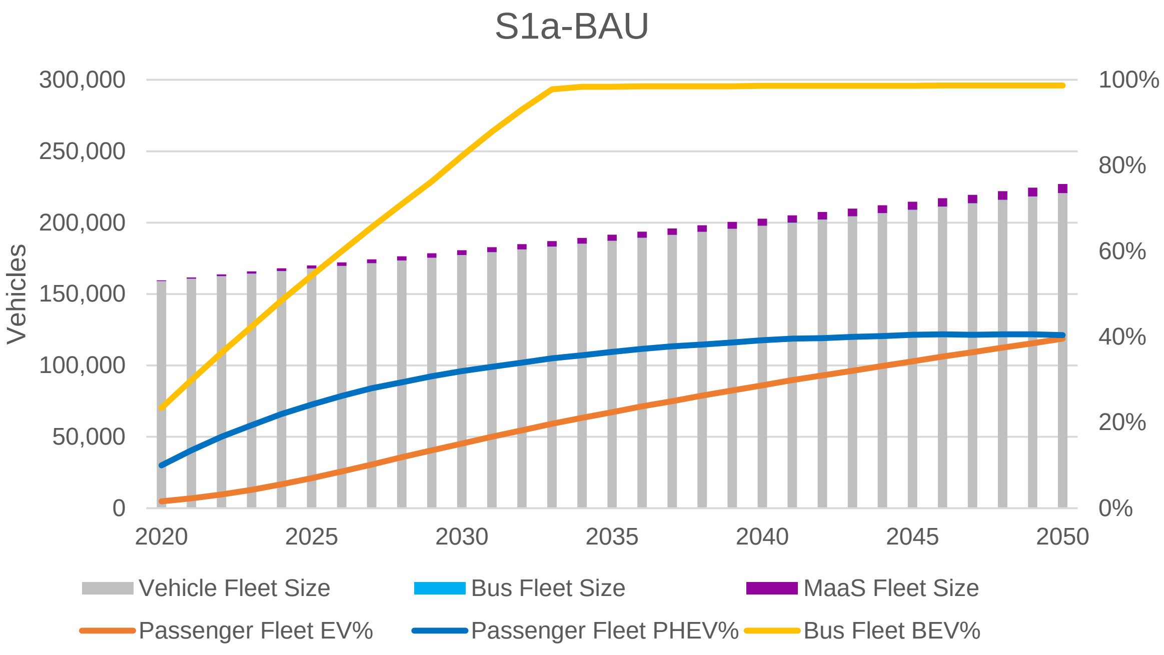


Figure 11: Changes in vehicle fleet variables in scenario S1a: business as usual without behavioral change

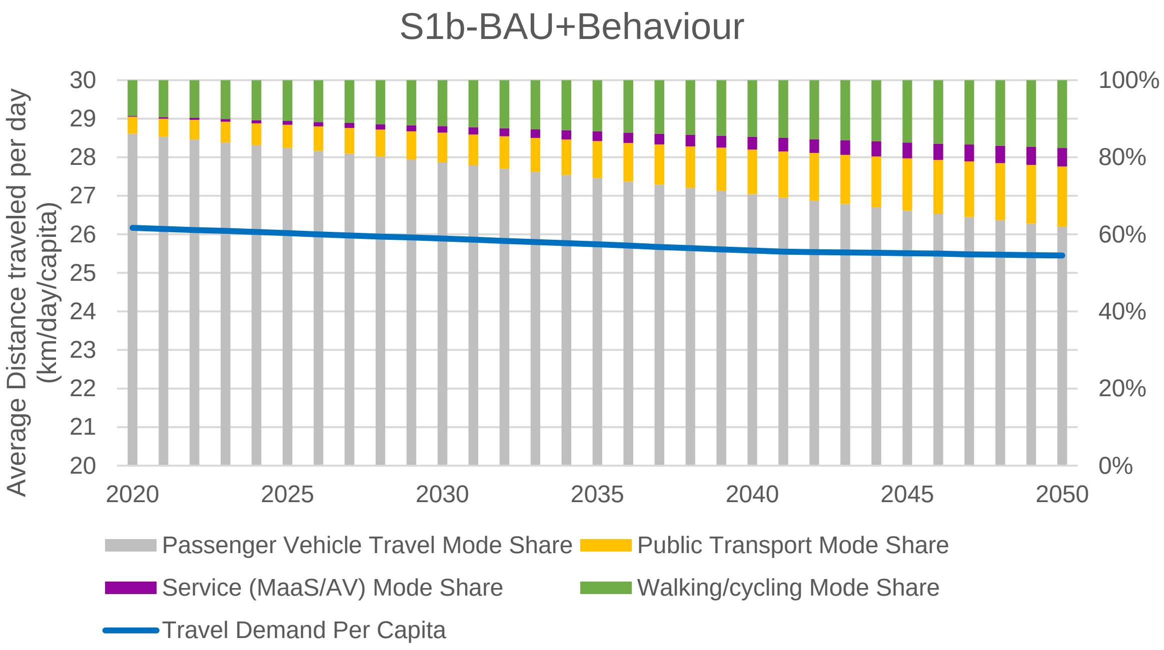


Figure 12: Changes in travel behavior variables in scenario S1b: business as usual with behavioral change.

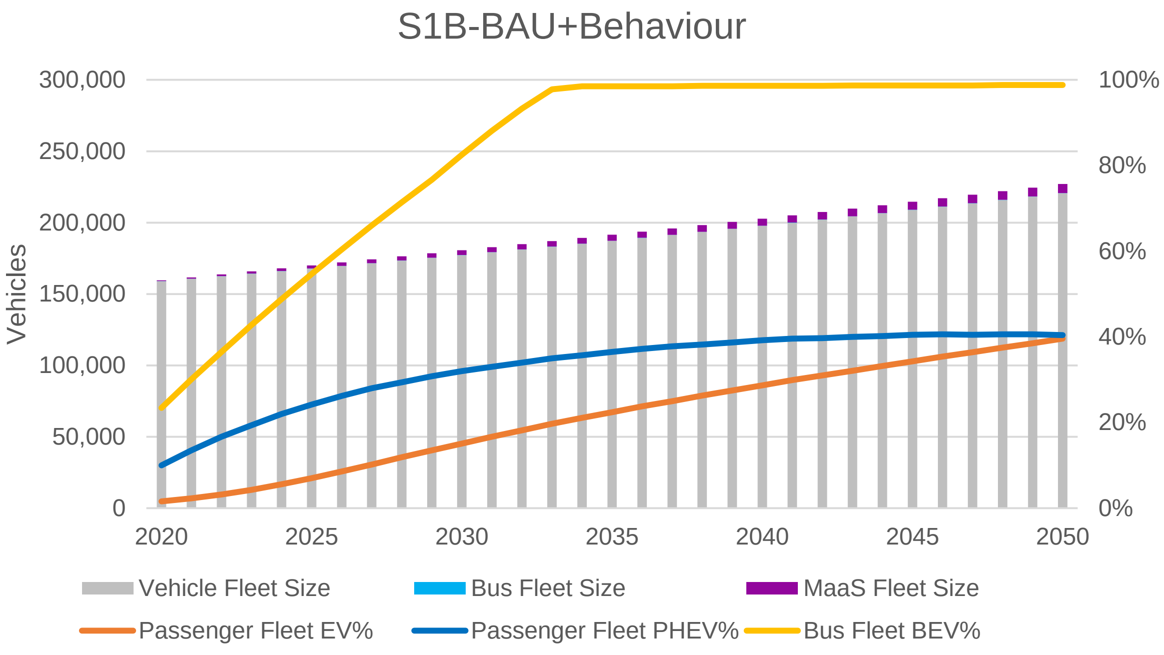


Figure 13: Changes in vehicle fleet variables in scenario S1b: business as usual with behavioral change.

S2: Urban Structural Change (USC)

Macro-scale developments

The scenario involves a moderate shift of predominant motivations towards reducing emissions and improving quality of life. This is mostly reflected in policies that support land use densification, and provision of public transport and cycling infrastructure. There is a moderate change in lifestyles and social norms towards environmental concerns and less consumption. There is public and political support for state interventions towards decarbonization in transportation and other sectors.

Changes in urban structure and transportation system

There is a strong focus on increasing the urban density in the region. Domestic airport area has been developed with a mixed-use & residential urban fabric with walkable street design and good access to services. This has increased the number and share of people living in close proximity to the main city center (less than 2 or 3 kilometers or the central pedestrian zone) and with ample provision of services in the neighborhood by more than 10000 people. Other areas close to the city center are also subject to densification.

By 2040, 70% of residents lives in places where PT access is good, in centres and transit oriented zones: 15% in Miðbær (up from 9%), 2% Smaralind and Mjódd (as it is now), 8% in other centers (up from 6%), 45% in transit oriented zones (up from 14%), and 40% in other parts of the city (in car-oriented zones). Travel times decrease in BRT corridors which led to some modal shift from cars. Car-centered infrastructure was developed at a slower pace that outlined in the regional master plan.

Borgarlína is fully developed by 2033, according to the plan. The rapid bus stations are surrounded with new multifunctional development forming local centers, whose residents can primarily use walking and public transportation. Public transportation is of higher quality (more accessible, reliable, frequent), but fares are relatively high and it has not gained universal popular support. Bus fares remain relatively expensive. Modal share and load factors of public transportation increase incrementally but rather slowly.

Changes in travel behavior and vehicle fleet

Decreased traffic distance required led to incremental decrease in travel demand (total number of traveled distances) and increase in walking, cycling and public transport modal shares. The average travel demand per person decreases to 25.23 km/day in 2030, 24.32 in 2040, and 23.44 by 2050. This results from shortened distances, improved accessibility, and convenience of using these travel modes, but is not strongly supported by urban policies. The rate of decrease is compatible with ranges predicted for similar scenarios in the U.S. and European cities described by Creutzig et al. (2012). PT mode share reaches 10% by 2030, 14% by 2040, and 18% by 2050. Mode share of cycling and walking combined reaches 12% by 2030, 15% by 2040, and 18% by 2050. Private care mode share drops to 76% in 2030, 67.5% by 2040, and 59% by 2050. The adoption of AVs and MaaS is slow and reaches 5% in 2050.

The car is still perceived as important for utilitarian and symbolic reasons. One reason is related to the necessity of using private cars for travel to destinations within the country. There are only limited restrictions on car use in the city, mostly related to pedestrianization of some of the downtown streets, and limited parking provision. The rate of car ownership decreases thanks to a higher number of people living in the city center and transit corridors, but there are no policies explicitly aimed at encouraging car-less lifestyles. As a result, car ownership reaches 655 cars per 1000 people by 2030, 602 by 2040, and 550 by 2050, thus achieving the rate of relatively compact U.S. and European cities of size similar to the Capital Region (e.g., Trieste, Italy; Boulder, Colorado; Savannah, Georgia; Szczecin, Poland; Gdańsk, Poland).

At first, the adoption of electric vehicles followed the recent trend. By 2030, the registration of new internal combustion engine vehicles (ICEVs) is banned and the adoption of EVs speeds up thanks to that. Battery electric passenger vehicles (BEV) comprise 16.7% of the fleet by 2030, 29.9% by 2040 and 40.6% by 2050. Hybrid and plug-in hybrid electric vehicles (HEV and PHEV) comprise 33% of the fleet by 2030, 39.6% by 2040 and 40.3% by 2050. There have been no diesel buses operating since 2032. By 2050, 98.75% of the buses are electric and 1.25% methane. The bus fleet is expanded according to the expansion of the BRT system to reach 160 buses by 2050.

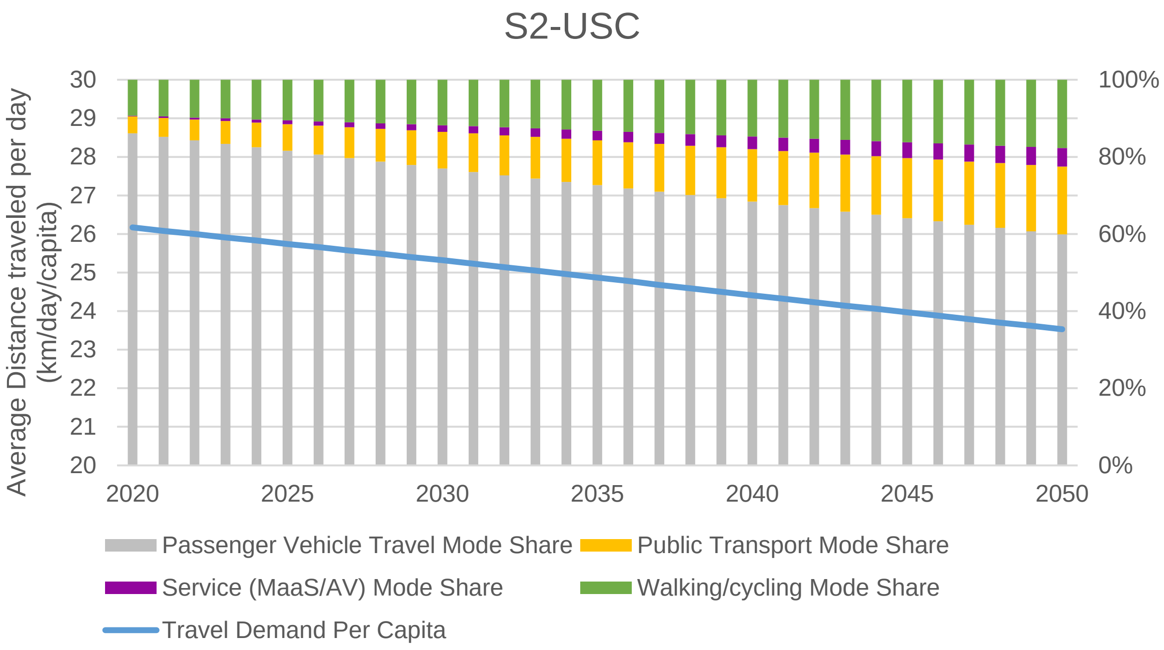


Figure 14: Changes in travel behavior variables in scenario S2: Urban Structural Change.

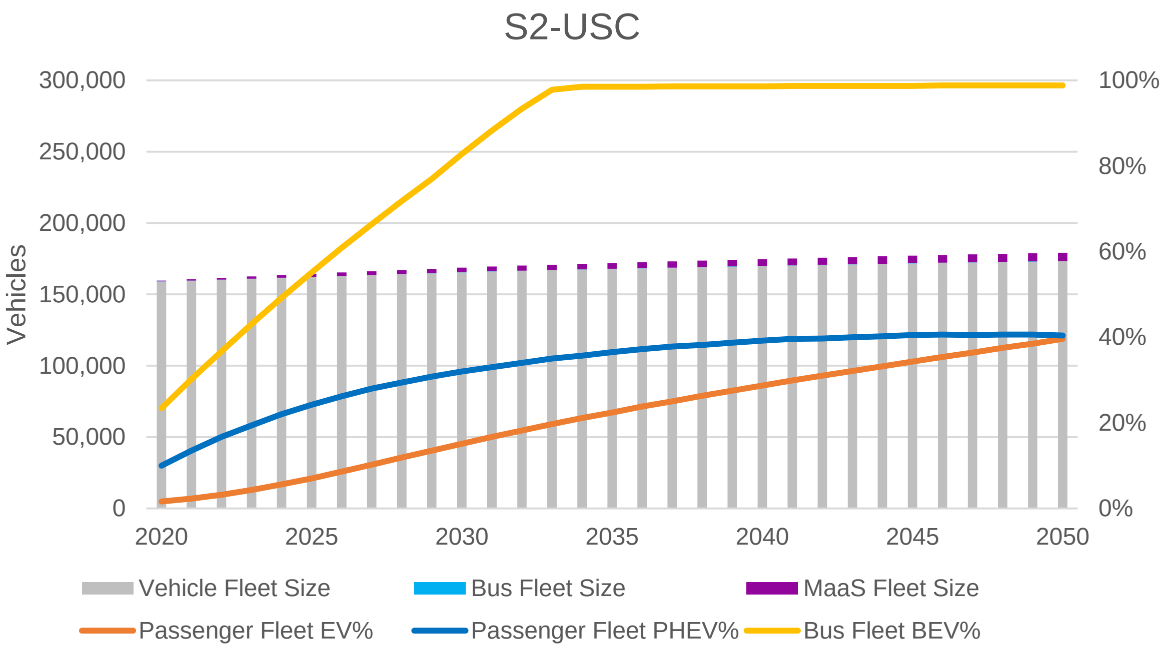


Figure 15: Changes in vehicle fleet variables in scenario S2: Urban Structural Change.

S3: Urban Structural & Lifestyle Change (USC+LS)

Macro-scale developments

The scenario involves paradigm change on a macro-scale away from economic growth towards reducing emissions and improving quality of life. This is reflected in policies at various levels and changes in lifestyles and social norms towards environmental concerns and less consumption. There are strong state interventions towards decarbonization in transportation and other sectors. International policies and funds exist to support decarbonization of local transport systems (e.g. funds to build PT and cycling infrastructure, replace bus fleet, subsidize private EVs). Fossil fuels are highly taxed. Subsequent elections lead to governments that are strongly pushing for decarbonization.

Changes in urban structure and transportation system

Like in the S2 scenario, there is a strong focus on increasing the urban density in the region. Domestic airport area has been developed with a mixed-use & residential urban fabric with walkable street design and good access to services. This has increased the number and share of people living in close proximity to the main city center (less than 2 or 3 kilometers or the central pedestrian zone) and with ample provision of services in the neighborhood, thus allowing for a higher share of walking and cycling trips for both commuting and non-commuting purposes. Other areas close to the city center are also subject to densification.

Borgarlína is fully developed by 2033, according to the plan. The rapid bus stations are surrounded with new multifunctional development forming local centers, whose residents can primarily use walking and public transportation. Public transportation is of much higher quality (more accessible, reliable, frequent) which strongly improves its reputation among residents, dramatically increasing the share of trips by bus. Thanks to national and international financial support for low-carbon public transportation, bus fares are eventually made free of charge (starting with lowering prices, making it free for school children and commuters, and then expanding).

Downtown areas and some of the sub-centers are strongly pedestrianized. Some car-oriented areas around shopping malls are refurbished to host multifamily housing and public spaces. There is a wide and well-connected network of cycling infrastructure. Changes in urban structure and infrastructure are accompanied with (and mutually reinforcing) changes in attitudes and public discourse related to travel. Cycling is in fashion, and residents acknowledge the social and health benefits of walking to places and living more localized lifes.

Changes in travel behavior and vehicle fleet

Radical changes in urban structure, lifestyles, and policies led to strong decrease in travel demand (total number of traveled distances). The average travel demand per person decreased to 24.86 km/day in 2030, 23.62 in 2040, and 22.44 in 2050. The change is compatible with predictions made for other European cities by Creutzig et al. (2012) assuming similar changes in urban structure and policies. The changes also led to an increase in walking, cycling and public transport modal shares. PT mode share reached 12% by 2030, 18% by 2040, and 24% by 2050. Mode share of cycling and walking combined reached 14% by 2030, 18% by 2040, and 22% by 2050. Reversal of pro-car attitudes among the population led to the support of more restrictive policies, such as downtown parking restrictions, car-free zones, and congestion charges in Reykjavik, further lowering the rate of car use. Private car mode share decreased to 72.1% by 2030, 60.5% by 2040, and 49% by 2050. The adoption of AVs and MaaS was slow and their mode share reached 5% in 2050.

The car is no longer a symbol of status, car-less lifestyles are commonly perceived as desirable, especially among young adults. Policies such as high-occupancy vehicle lanes were implemented to promote car sharing in the city. Owning a car is no longer perceived as necessary for domestic travel, thanks to improvements in public transportation and collective ownership of cars, for instance through trade unions. Policies aiming at increasing the cost of car ownership have been implemented. As a result, car ownership rates dwindle, with most purchases related to replacing old cars with new subsidized EVs. Car ownership decreases compared to the 2019 level and reaches 450 cars per 1000 people, which is a level compatible with some of the more compact and less car-dependent cities in Europe and the U.S., such as Vitoria-Gasteiz, Spain; Bydgoszcz, Poland; Oulu, Finland; Stavanger, Norway; New Haven, Connecticut.

At first, the adoption of electric vehicles followed the recent trend. By 2030, the registration of new ICEVs is banned and the adoption of EVs speeds up thanks to that. Battery electric passenger vehicles (BEV) comprise 16.7% of the fleet by 2030, 29.9% by 2040 and 40.6% by 2050. Hybrid and plug-in hybrid electric vehicles (HEV and PHEV) comprise 33% of the fleet by 2030, 39.6% by 2040 and 40.3% by 2050. There have been no diesel buses operating since 2032. By 2050, 98.75% of the buses are electric and 1.25% methane. The bus fleet is expanded according to the expansion of the BRT system to reach 160 buses by 2050.

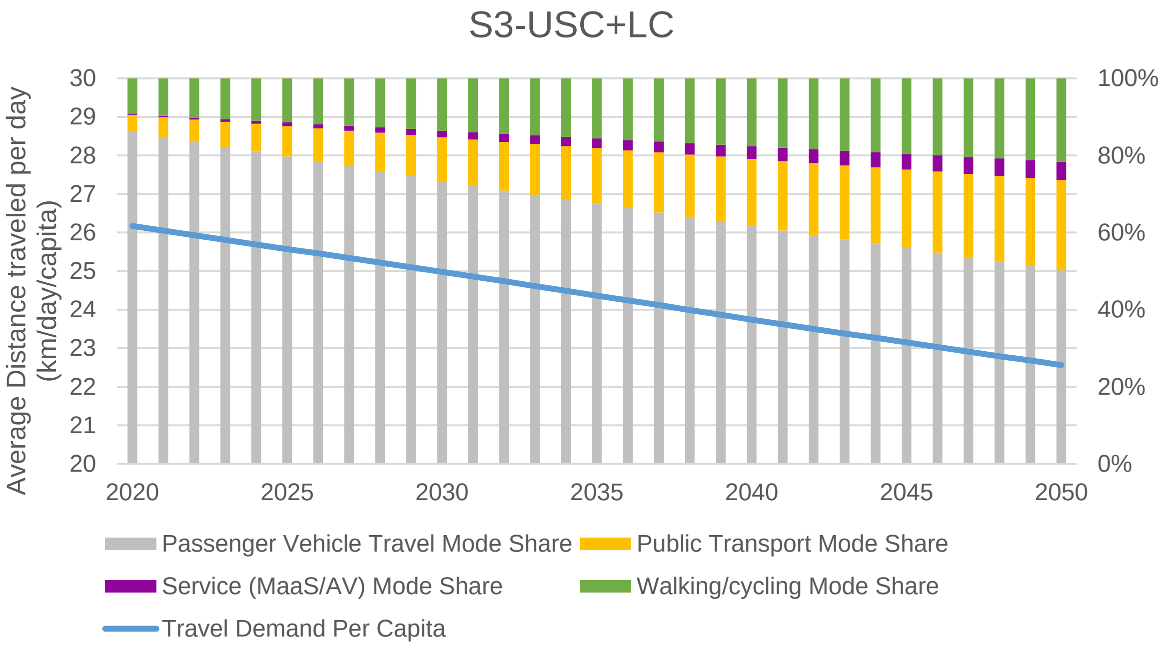


Figure 16: Changes in travel behavior variables in scenario S3: Urban Structural Change and Life Style Change.

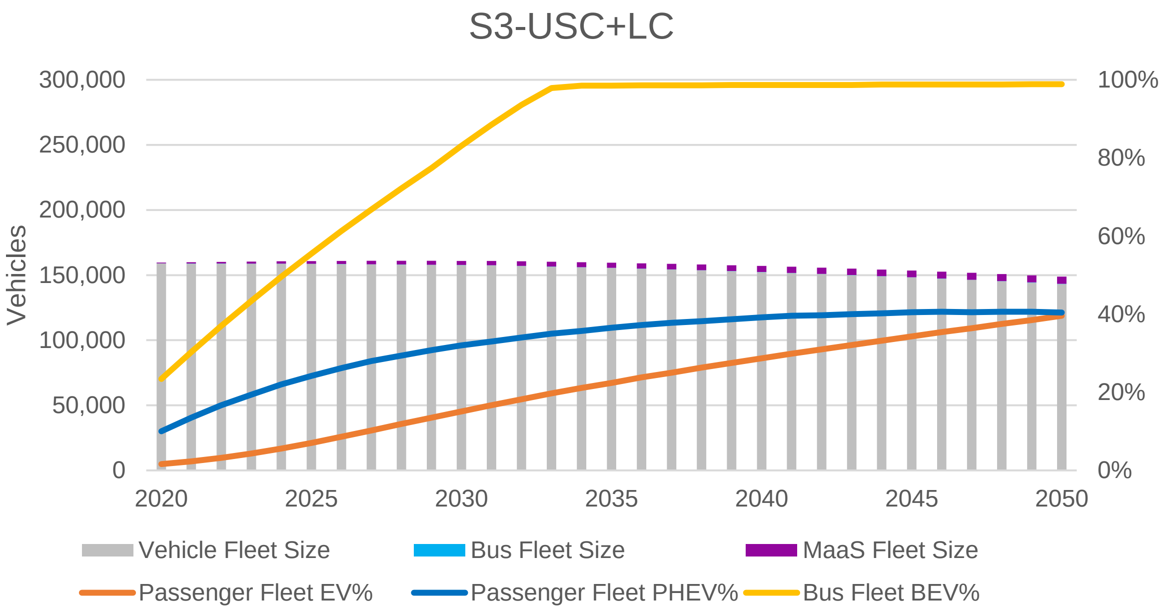


Figure 17: Changes in vehicle fleet variables in scenario S3: Urban Structural Change and Life Style Change.

S4: Technological Changes (Tech)

Macro-scale developments

The scenario aims at rapid reduction in emissions through technological developments, mainly through a massive adoption of electric vehicles and buses, improvement in the efficiency of the vehicle fleet as well as a considerable growth in Mobility-as-a-Service systems. Considering the general public's interest to cut emissions quickly, the government will provide supportive incentives to facilitate the adoption of electric cars, and electric buses. Considering the fact that the attitude of people towards car ownership is changing, there will be public support for government interventions to shape the transport system based on new digitized mobility solutions (multimodal Mobility as a Service (MaaS), car sharing, etc.).

Changes in urban structure and transportation system

The scenario does not involve any major changes on a macro-scale. There is a slow and gradual increase of the emphasis on reducing emissions, following current trends. This is reflected in policies at various levels but these are not very radical, and there is only some change in lifestyles and social norms towards environmental concerns and less consumption. There are some state interventions towards decarbonization in transportation and other sectors. Subsequent elections lead to governments that follow current policies but with differing strength and success.

Changes in urban structure and transportation system

Changes in urban structure and the public transportation system follow the pattern from S1a scenario. Borgarlína is fully developed by 2033. Urban densification is mostly concentrated around Borgarlína stations, and there is much less densification of the urban area close to the city center. The domestic airport area is not developed. Travel times decrease in Borgarlína corridors and reliability of bus travel is improved, which leads to a moderate modal shift from cars. At the same time, car infrastructure is continuing to be developed and there are no major restrictions or disincentives regarding car ownership and use, which slows down further changes in travel behavior.

The main focus of this scenario is to utilize various innovative technologies to reduce the environmental impact of the transportation sector. The transition to electro-mobility has already started both in light-duty vehicles and public buses. Yet, it's projected that due to government supportive policies, the transition happens faster and we can observe massive adoption of electric vehicles as well as electric buses. Currently, the tax reform proposal (Alþingi, 2010, Ministry of Finance and Economic Affairs, 2018) has proposed to increase the excise duty tax and road tax for conventional vehicles, while providing tax breaks for the purchase of electric vehicles. In this scenario, we also explored the impact of the continuation of the VAT exemption policy for electric vehicles after 2020. Besides, considering the national climate targets, the impact of imposing a ban on the new sales of ICE and HEV from 2025 on GHG emissions from passenger transportation in Reykjavik will be studied. In addition, it is projected that due to government' push and public's concerns, vehicle manufacturers will try to further increase the efficiency of new vehicles.

Recently, it was observed that issues such as the cost of ownership and lack of flexibility, are influencing consumer attitude in a way that could significantly impact individual car ownership. Besides, awareness and usage of ride-hailing, car-sharing, and vehicle subscription services – not to mention self-driving cars – is growing and new transportation models will continue to emerge. Considering the potential of MaaS in reducing congestion on urban roads, improving air quality from a reduction in CO2 and NO2 emissions and decreasing the need to invest in infrastructure including parking space, there will be public support for government interventions to shape the transport system based on new solutions, including MaaS. Policy instruments for substituting car ownership with mobility services can be classified into "soft" and "hard" measures. Soft measures include information campaigns on mobility options, awareness campaigns on the impacts and costs of different travel modes and travel planners, while hard measures include laws, rules, taxes, subsidies and financing. Examples include e.g. increasing taxes for private car use, changes in land use policy (e.g. regarding parking or roads), charging road tolls for entering congested areas, or giving subsidies for the use of shared mobility services (Laine 2018).

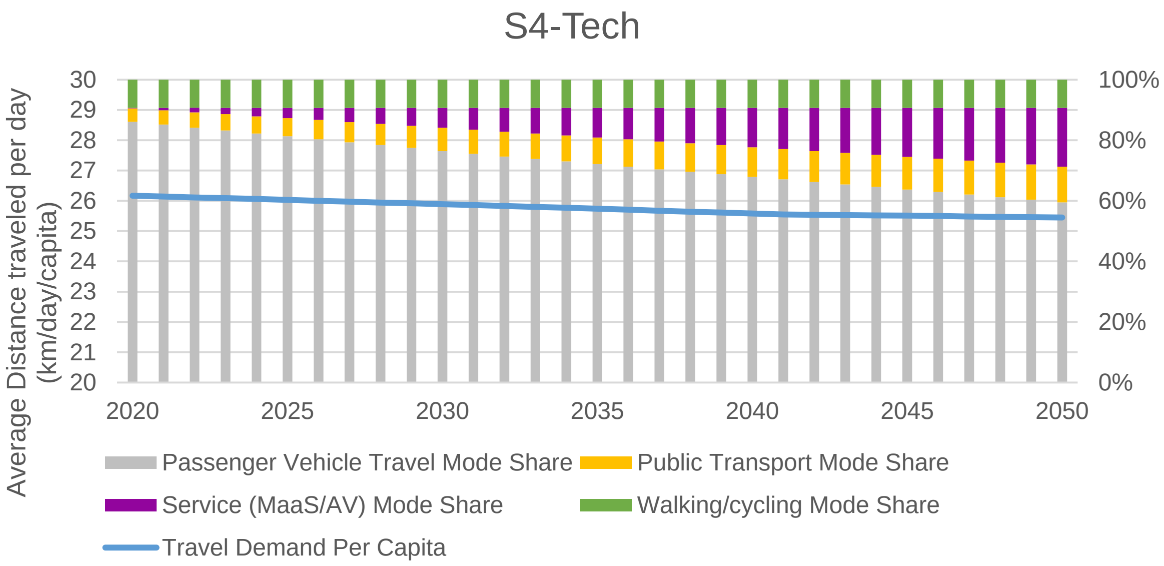


Figure 18: Changes in travel behavior variables in scenario S4: Technological Change.

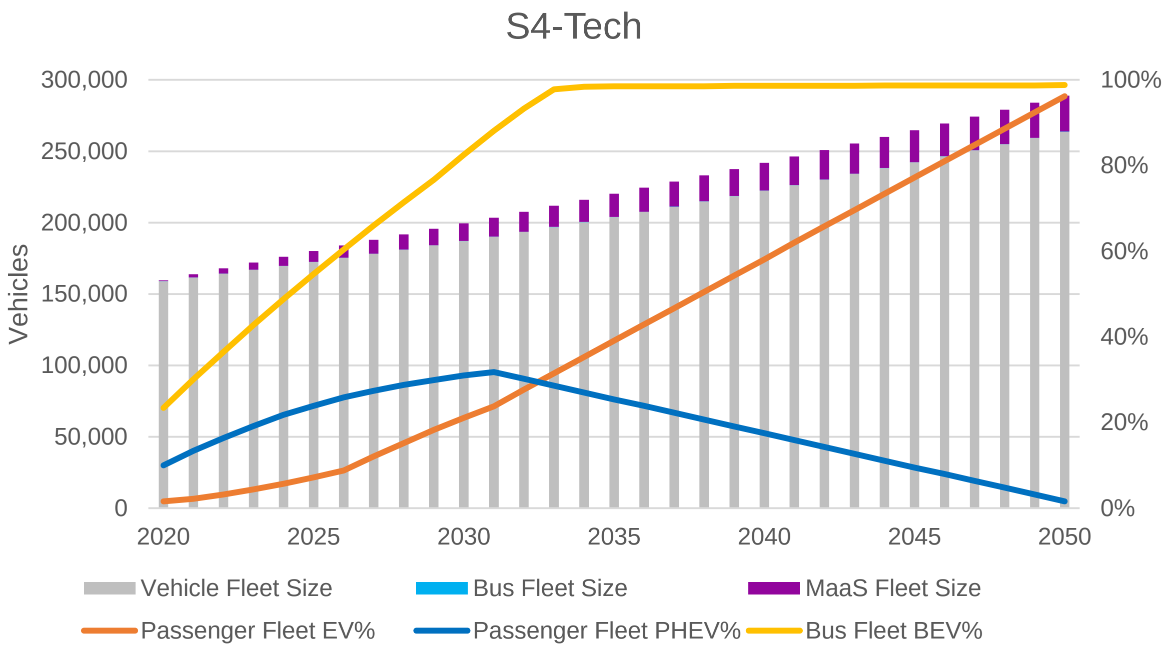


Figure 19: Changes in vehicle fleet variables in scenario S4: Technological Change.

S5: Integrated Approach Scenario

Macro-scale developments

The scenario involves paradigm change on a macro-scale away from economic growth towards reducing emissions and improving quality of life. This is reflected in policies at various levels and changes in lifestyles and social norms towards environmental concerns and less consumption. There are strong state interventions towards decarbonization in transportation and other sectors. International policies and funds exist to support decarbonization of local transport systems (e.g. funds to build PT and cycling infrastructure, replace the bus fleet, subsidize private EVs). Fossil fuels are highly taxed. Subsequent elections lead to governments that are strongly pushing for decarbonization.

Changes in urban structure and transportation system

Like in the S2 & S3 scenarios, there is a strong focus on increasing the urban density in the region. Domestic airport area has been developed with a mixed-use & residential urban fabric with walkable street design and good access to services. This has increased the number and share of people living in close proximity to the main city center (less than 2 or 3 kilometers or the central pedestrian zone) and with ample provision of services in the neighborhood, thus allowing for a higher share of walking and cycling trips for both commuting and non-commuting purposes. Other areas close to the city center are also subject to densification. Due to the progress in the densification of some urban areas, the travel demand has first stabilized and then significantly reduced due to the massive changes in the forms of urban areas.

Borgarlína is fully developed by 2033, according to the plan. The rapid bus stations are surrounded with new multifunctional development forming local centers, whose residents can primarily use walking and public transportation. Public transportation is of much higher quality (more accessible, reliable, frequent) which strongly improves its reputation among residents, dramatically increasing the share of trips by bus. Thanks to national and international financial support for low-carbon public transportation, the bus fleet is predominantly electric and bus fares are eventually made free of charge (starting with lowering prices, making it free for school children and commuters, and then expanding).

Downtown areas and some of the sub-centers are strongly pedestrianized. There are safe and comfortable conditions for pedestrians in densely built areas. Some car-oriented areas around shopping malls are refurbished to host multifamily housing and public spaces. New car infrastructure is defunded.

Changes in urban form and access to public transportation coincide with and foster changes in attitudes (a positive feedback) thus facilitating a transition to a different urban mobility culture (Klinger et al. 2013). Positive attitudes towards walking and urban walkability increase willingness to walk to work and non-commuting destinations. An increasingly high proportion of people are willing to move to central and walkable locations that support car-less lifestyles (this requires affordable housing close to the city center and major job concentrations). There is broad public support for further densification of the city center (including the domestic airport area). An increasingly smaller proportion of the population is willing to live in a suburban setting. People who move to the Capital Region from abroad or the countryside are no longer "coerced" into a car-oriented culture.

There is a wide and well-connected network of cycling infrastructure. Changes in urban structure and infrastructure are accompanied with (and mutually reinforcing) changes in attitudes and public discourse related to travel. Public discourse is increasingly in favor of buses, walking, and cycling. Positive attitudes towards cycling increase the popularity of this travel mode among the able-bodied residents. Cycling is in fashion, and residents acknowledge the social and health benefits of walking to places and living more localized lifes. Urban and car-less lifestyles proliferate.

Environmental and climate change awareness strengthens preference for low-carbon travel modes. Reducing personal emissions becomes one of the primary decision-making factors among the majority of the population. There is broad public support for mitigation policies, including taxes and caps.

The car is no longer a symbol of status, car-less lifestyles are perceived as desirable, especially among young adults. Car ownership rates dwindle, with most purchases related to replacing old cars with new subsidized EVs. Policies such as high-occupancy vehicle lanes are implemented to promote car sharing in the city. Owning a car is no longer perceived as necessary for domestic travel, thanks to improvements in public transportation and collective ownership of cars, for instance through worker unions. Policies aiming at increasing the cost of car ownership have been implemented. An increasingly higher proportion of young people is not getting a driver's license. This is reinforced by MaaS offer in domestic (e.g. for visiting summer houses etc.) and local travel (getting big shopping, or just a more comfortable commute than with buses). There are communal car sharing services. For instance, it is possible to rent an electric car from a workers' union for a low price to get to a summer house.

Reversal of pro-car attitudes led to support of more restrictive policies, such as parking restrictions, car-free zones, and congestion charges in Reykjavik. Radical changes in urban structure, lifestyles, and policies led to strong decrease in travel demand (total number of traveled distances), increase in walking, cycling and public transport modal shares, decreased car ownership, and increased load factors in private cars and buses.

Awareness and usage of ride-hailing, car-sharing, and vehicle subscription services (including self-driving cars) is growing and new transportation models continue to emerge. Advanced technologies like AVs and MaaS start to be more practical. Intelligent transport solutions are introduced, and people will be able to use mobile apps to book and pay in one click for any trip by bus, train, taxi, bicycle, and/or car sharing. Considering the potential of MaaS in reducing congestion on urban roads, improving air quality from a reduction in CO2 and NO2 emissions and decreasing the need to invest in infrastructure including parking space, there is strong public support for government interventions to shape the transport system based on new solutions, including MaaS. Eventually, MaaS forms a coherent system with public transport, that is efficient and available for all to use.

There are strong subsidies for EV purchase in case of replacing conventional vehicles. Consumer preferences for EVs over combustion vehicles increase the penetration of EVs significantly and rapidly. Due to the ban on the import of ICEs after 2030, the fleet of electric vehicles grows considerably. Due to the massive integration of cheap, reliable MaaS, the use of old vehicles running on fossil fuel decreased significantly. Figure 20 shows the projected changes in travel demand and the mode shares until 2050 in S5 Integrated Approach It's expected that the travel demand will significantly decrease due to increase in urban density and a considerable shift away from using private cars to public transport, cycling and walking.

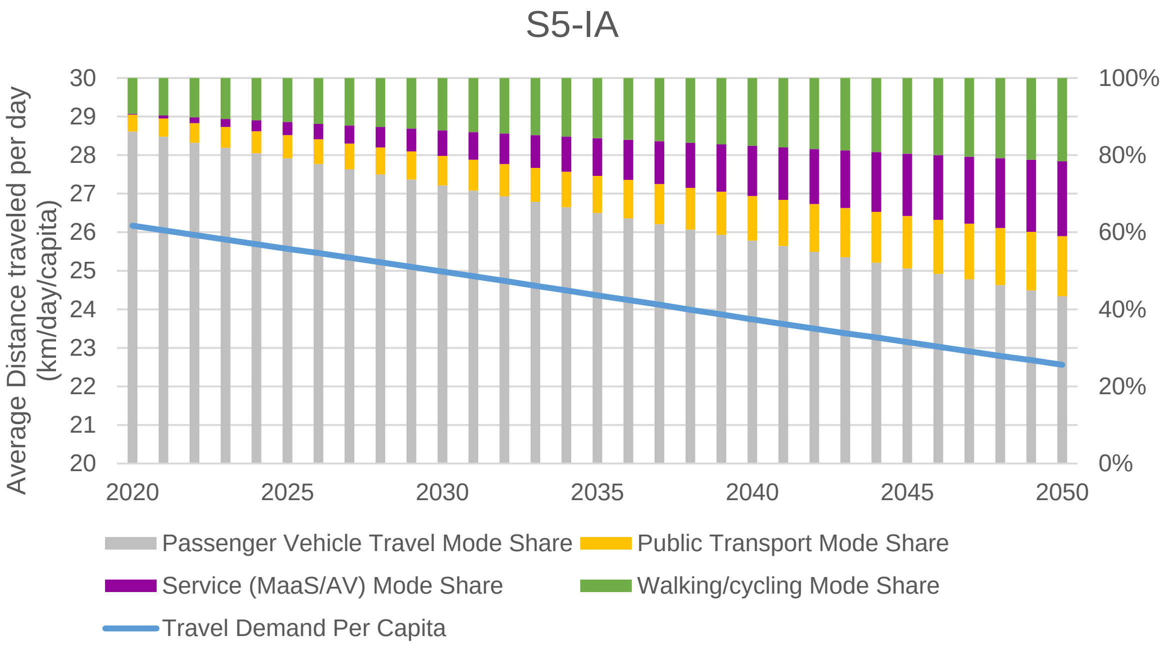


Figure 20: Changes in travel behavior variables in scenario S5: Integrated Approach.

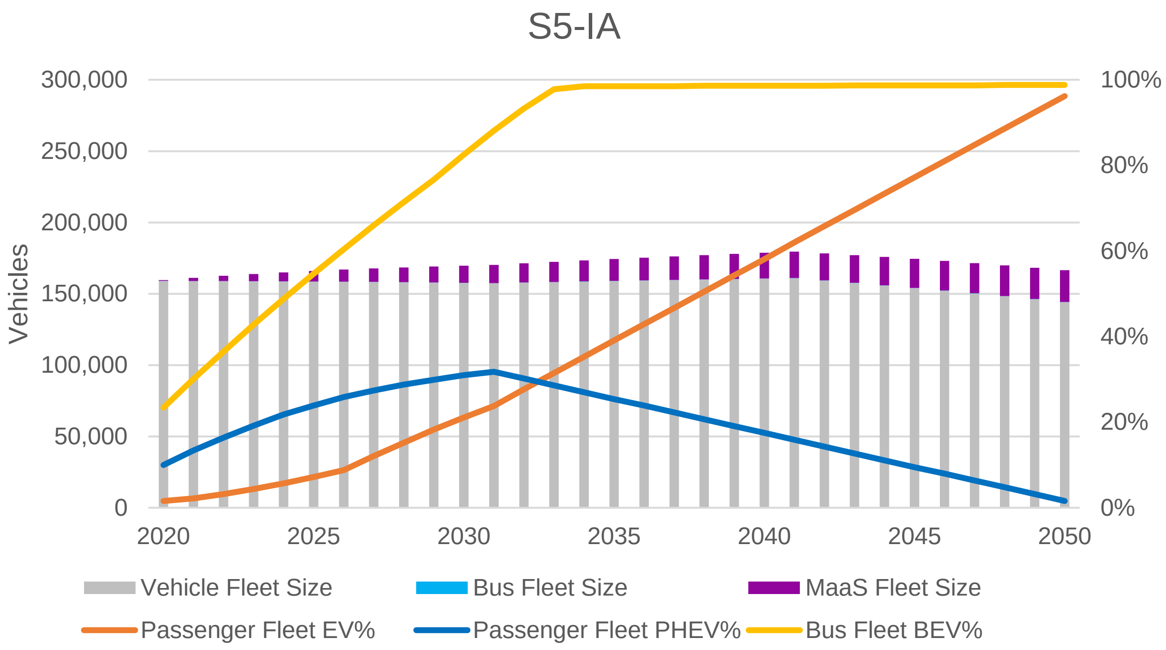


Figure 21: Changes in vehicle fleet variables in scenario S5: Integrated Approach.

S6: Worst- Case Scenario

Macro-scale developments

The scenario involves a strong shift in paradigms that influence climate change and transportation related policies. The efforts to mitigate climate change are first ignored and then abandoned. The economy contributes to rising inequalities, with fast growth in some places and social groups and deterioration in others. A "Trumpist" approach to government proliferates. Political parties that are against state intervention and international cooperation and openly deny climate change come to power. There is little to no international or national funding that would support decarbonization of local transport systems. Fossil fuels are not highly taxed, but gradually become more expensive due to resource depletion.

Changes in urban structure and transportation system

Urban densification is continued only selectively, wherever it is profitable to develop downtown apartments and hotels, and urban sprawl is not constrained. Domestic airport keeps its function. One reason is to serve an increasing number of private planes of the elites. There is no clear plan to promote public transport and urban policies fail due to inconsistent planning. Eventually, Borgarlína development was halted and never completed. Public transportation is increasingly perceived as inefficient and a "handout to the poor", which leads to decreasing modal share and worsening reputation of buses. There are few investments in cycling infrastructure.

Changes in travel behavior and vehicle fleet

Private cars remain the predominant travel mode. The car remains the symbol of status and is increasingly perceived as necessary for survival, especially with deterioration of public safety and extreme weather events. SUVs with a 4WD system have become the most commonly bought new models. Suburban and car-dependent lifestyles proliferate. There is little public support for constraining suburban development, especially among the wealthy and powerful elites.

As a result, the average travel demand per person increases to 28.3 km/day by 2050. PT mode share decreases to 4% by 2030, 3% by 2040, and 2% by 2050. Mode share of cycling and walking combined decreases to reach 9% by 2030, 8% by 2040, and 7% by 2050. Private care mode share remains at around 86%, similarly as in 2019, thanks to a slow adoption of AVs and MaaS, whose mode share reaches 5% in 2050.

Car ownership steeply increases compared to the 2019 level and reaches 754 cars per 1000 people by 2030, 800 by 2040, and 847 by 2050, which is a level of some car-dependent cities in the U.S. (e.g. Provo, Utah or Oxnard, California). With an increase of population, that means an increase of the fleet by about 100 thousand cars by 2050.

The ban on registering combustion cars is lifted, there are no subsidies for EV purchase. EVs increase their market share due to lowering prices of cars and increasing prices of gasoline. But at the same time, due to the improved fuel economy of ICEs, the rate of EV adoption is slow. Eventually, due to technical and political challenges, the rate of EV adoption stabilized. The share of battery electric passenger vehicles (BEV) reaches 16.7% of the fleet by 2030 and stabilizes. Similarly, hybrid and plug-in hybrid electric vehicles (HEV and PHEV) reach 33% of the fleet by 2030 and stabilize at this level until 2050. There have been no diesel buses operating since 2032. By 2050, 98.64% of the buses are electric and 1.36% methane. The bus fleet is slowly increased to reach 147 buses by 2050.

There are major challenges to execute MaaS businesses as there is insufficient financial support to promote new technologies. Due to the negative word-of-mouth effect from the bad experience with AVs and MaaS, the business fails to reach the level that can lower the cost of transport to make it interesting for consumers. The mode share of AVs and MaaS reaches 5% in 2050.

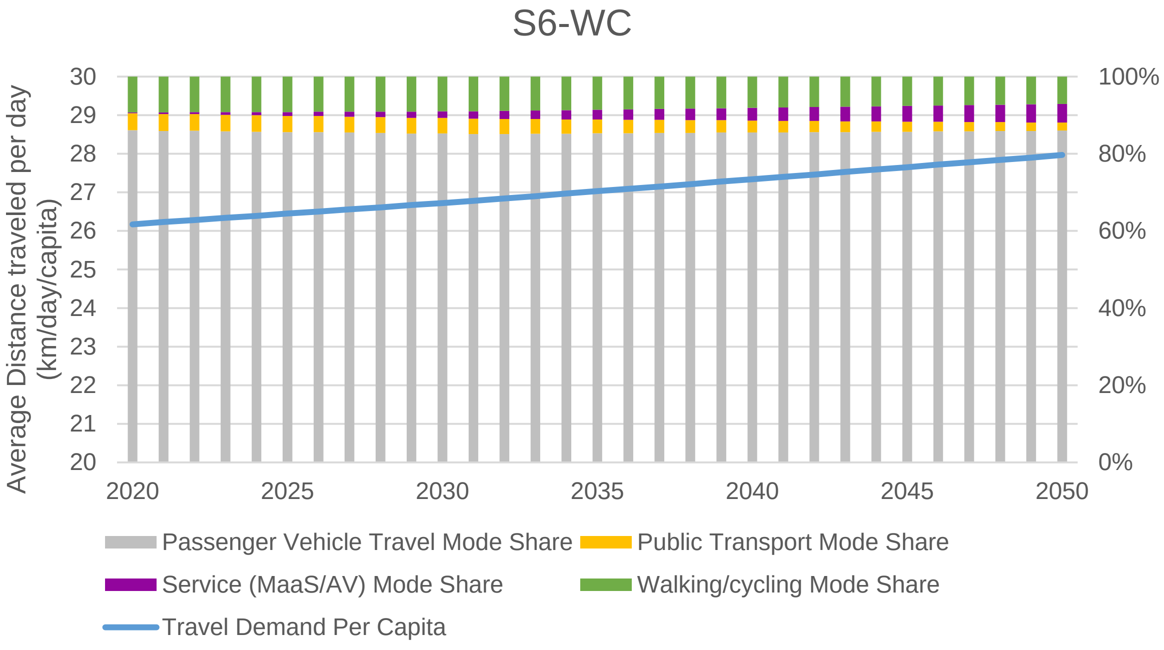


Figure 22: Changes in travel behavior variables in scenario S6: Worst Case.

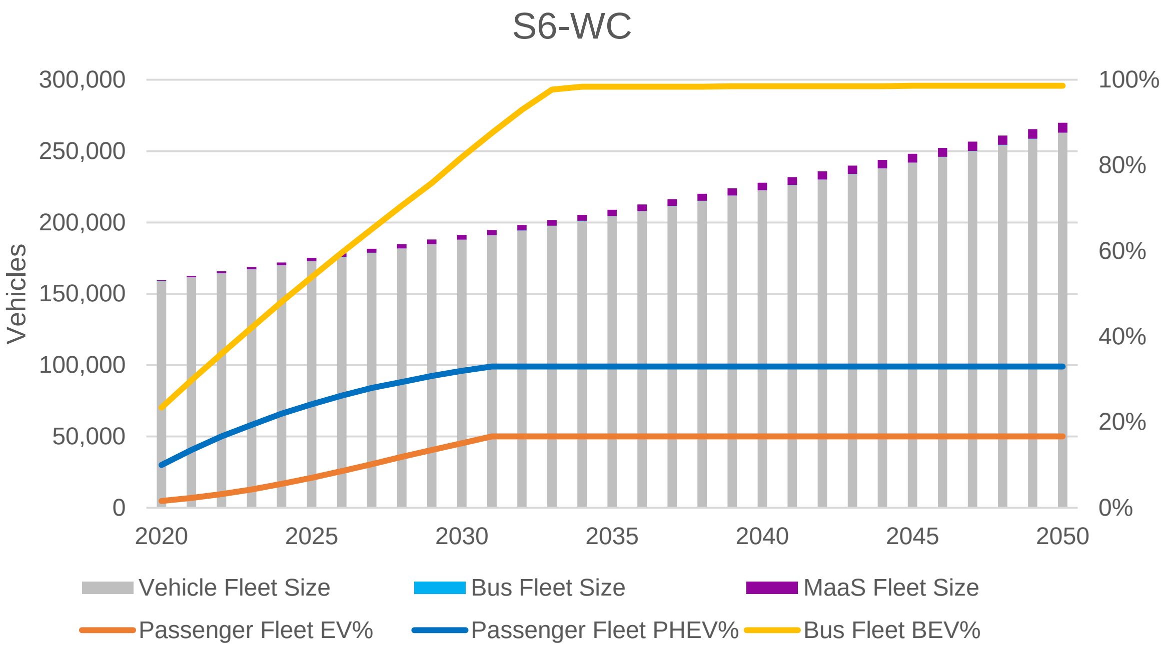


Figure 23: Changes in vehicle fleet variables in scenario S6: Worst Case.

S7. Radical change scenario

Macro-scale developments

The scenario starts from the presumption that the humanity notices climate change becoming such a threat that it needs to be stopped with rapid and profound changes in the society at all levels. Iceland commits to international treaties demanding rapid global decarbonization, in which countries are not responsible only for the emissions occurring within their national boundaries, but also for the indirect emissions occurring due to the use of imported goods and services. In the urban planning and transport sectors this leads to strong restrictions to private car use, fiscal disincentives to possessing and operating vehicles, and incentives to MaaS, public transport and active modes of travel. These policies and changed conditions shape the behaviors so that vehicle possession goes down rapidly and dramatically, travel demand decreases significantly, and Maas, PT and active modes create the modal split.

Changes in urban structure and transportation system

Urban density, walkability, cycling infrastructure and local service provision are the nexus of development. The city center is closed from private cars and only allowed for active modes and PT. The majority of streetside parking across the whole region is erased and the space is used for cycling lanes. The whole region is served by electric city bicycles free of charge for all residents. PT is made free of charge. Larger parking lots are used for infill development for a major part. The remaining few parking spaces are expensive and only used by those urgently needing private cars, typically for trips away from the region. MaaS serves for trips outside PT services and not taken with the electric city bicycles. Domestic airport area has been developed with a mixed-use & residential urban fabric with walkable street design and good access to services.

Borgarlína is fully developed by 2033, according to the plan. Main borgarlina stations are used as hubs served by buses from further away locations, as well as the city-wide electric bicycle system. The rapid bus stations are surrounded with new multifunctional development forming local centers, whose residents can primarily use walking and public transportation. Public transportation is of much higher quality (more accessible, reliable, frequent) which strongly improves its reputation among residents, dramatically increasing the share of trips by bus.

In addition to the downtown areas, the main sub-centers are strongly pedestrianized. Some car-oriented areas around shopping malls are refurbished to host multifamily housing and public spaces. There is a wide and well-connected network of cycling infrastructure. MaaS is reliable and significantly cheaper than possessing and operating a private vehicle, even for trips away from the city.

The strong push towards de-motorization and the accompanied changes in the infrastructure for PT and active modes, especially cycling, accompanied with the global climate emergency rapidly change attitudes related to travel. Floods following the global sea level rise start threatening Reykjavik city center and make it very tangible that all possible actions need to be taken to stop warming before the damage is too high and unbearable. Cycling becomes the fashion, overall travel demand goes down due to improved local services and increased distant working and learning. The environmental, social and health benefits of active transport and more localized living are appreciated by the residents.

Changes in travel behavior and vehicle fleet

The above described radical changes in the service-levels and costs of different transport modes, urban structure, lifestyles, and policies reduce travel demand radically (total traveled distance). The average travel demand per person decreased to 22 km/day in 2030, 20 in 2040, and 16 in 2050. The changes also led to an increase in walking, cycling, public transport and MaaS modal shares, up to nearly disappearance of private cars and driving. PT mode share reached 15% by 2030, 25% by 2040, and 40% by 2050. Mode share of cycling and walking combined reached 20% by 2030, 30% by 2040, and 40% by 2050. Maas share reaches 6% by 2030, 10% by 2040 and 15% by 2050. Private car mode share decreased to 59% by 2030, 35% by 2040, and 5% by 2050.

The car is no longer a symbol of status, but rather a symbol of selfishness and ignorance. MaaS services are subsidized and particularly along with automation of driving (driverless vehicles) exceeds the service-level of personally possessed vehicles. As the result, car ownership decreases significantly and ultimately reaches 50 cars per 1000 people level by 2050. The number of automated MaaS vehicles serving the city reach 100 cars per 1000 people by 2050.

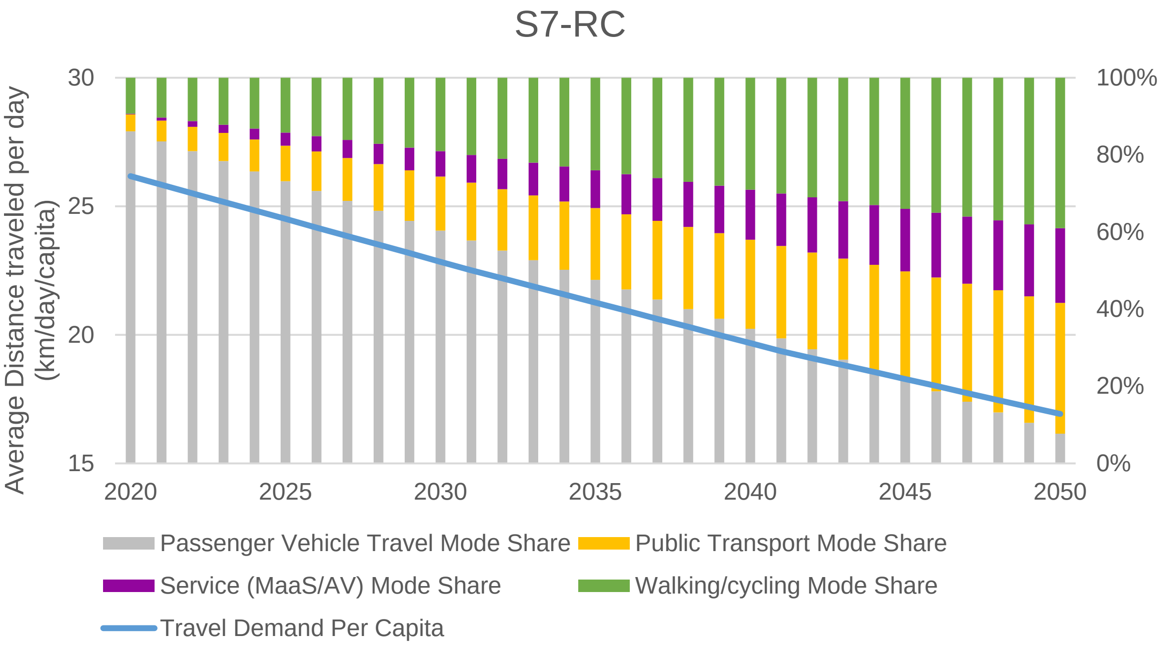


Figure 24. Changes in travel behavior variables in scenario S7: Radical Change Scenario

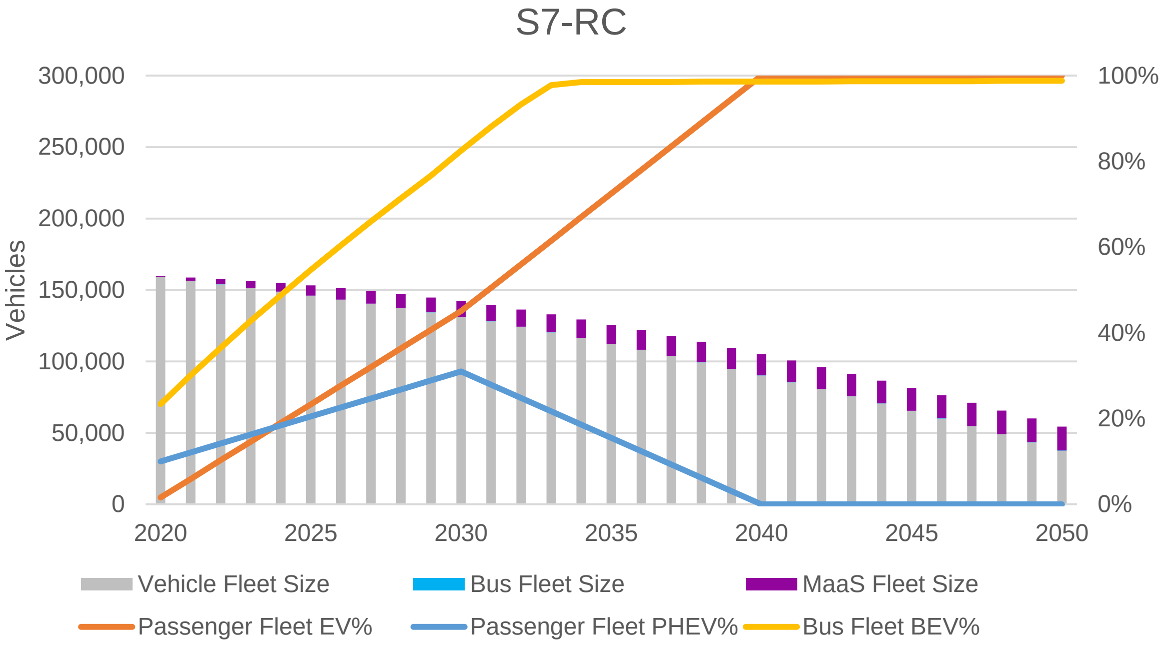


Figure 25. Changes in vehicle fleet variables in scenario S7: Radical Change Scenario

Results and Discussions

The total (direct plus indirect) GHG emissions for all scenarios, have been estimated using the model, described earlier (Figure 26).

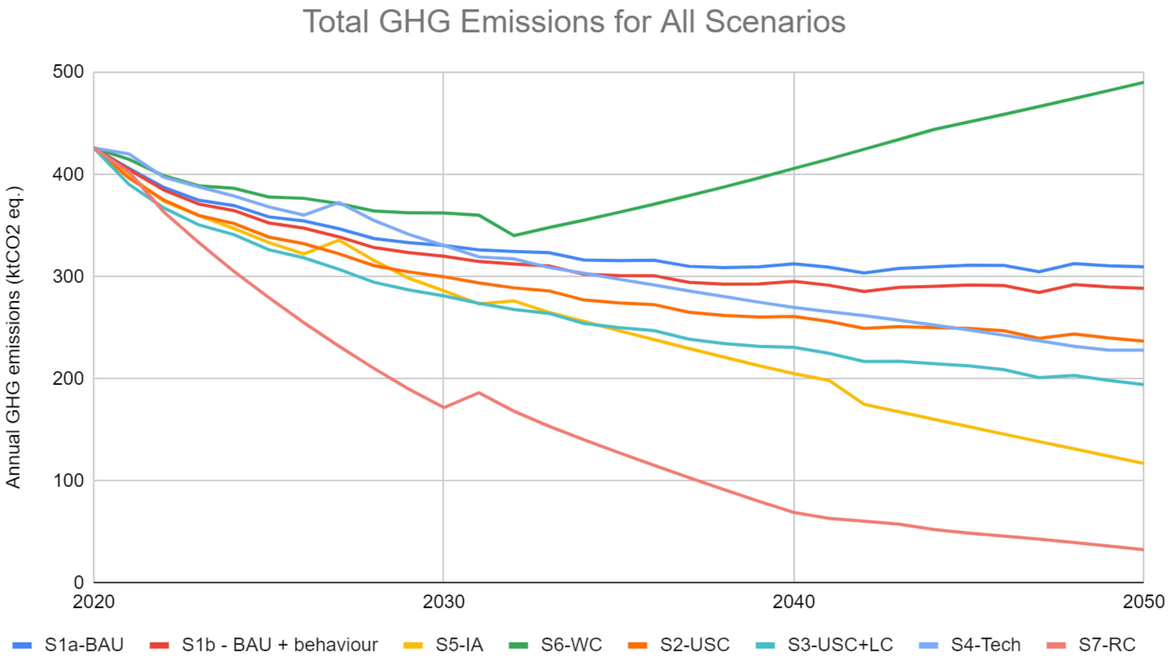


Figure 26: Total (direct plus indirect) annual GHG emissions for all scenarios from 2020-2050.

Except for S3 (the worst case), in which there will be an increase in car ownership, we observe a gradual decrease in total emissions across all other scenarios until 2030-2035 period. After that, there is a clear difference between the trends of total emissions. For instance, the decreasing trend stabilizes in four scenarios, BAU, BAU+ behavior, USC and USC+LC. On the other hand, the Tech scenario shows a rather continuous reduction in total GHG emissions. The Integrated Approach scenario which includes a diverse set of policies and changes across key transport related domains, show the most promising output behind the S7 Radical Change Scenario, in terms of rapid reduction in total GHG emissions which reaches 100 kilotons of CO_2 equivalent (kt CO_2-eq.) in 2050. The Radical Change scenario however leads to the lowest annual GHG emissions throughout the entire time period. The resulting cumulative emissions from each scenario can be seen below in Figure 27.

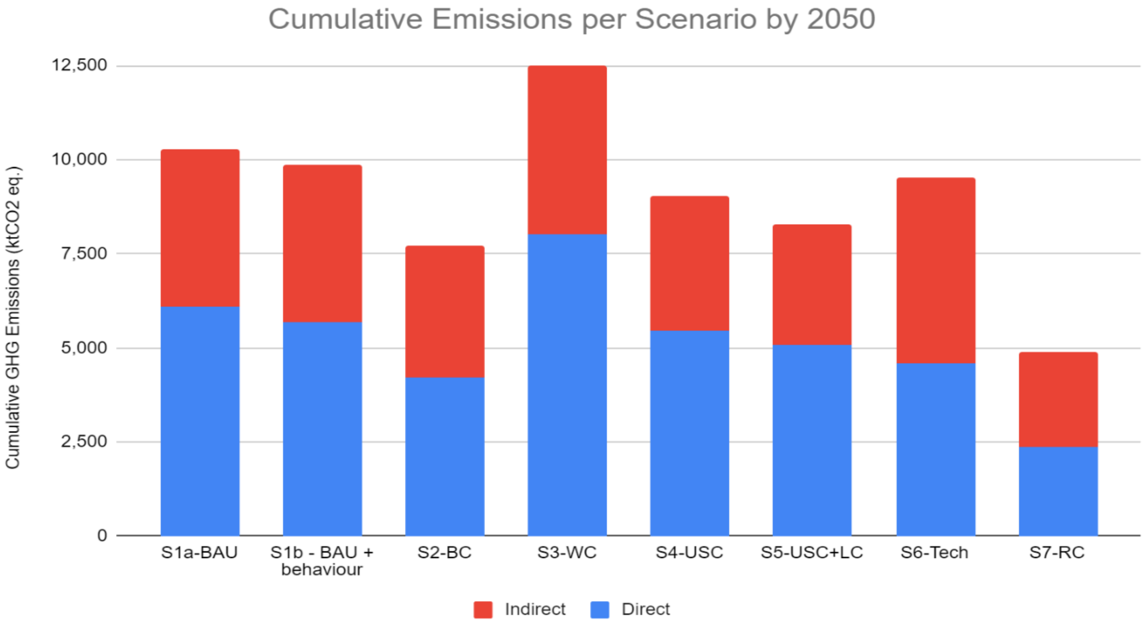


Figure 27: The cumulative emissions (divided by direct and indirect) until 2050 for all scenarios

Figure 28 and 29 show the annual direct and indirect GHG emissions for all scenarios in kt CO_2-eq, respectively.

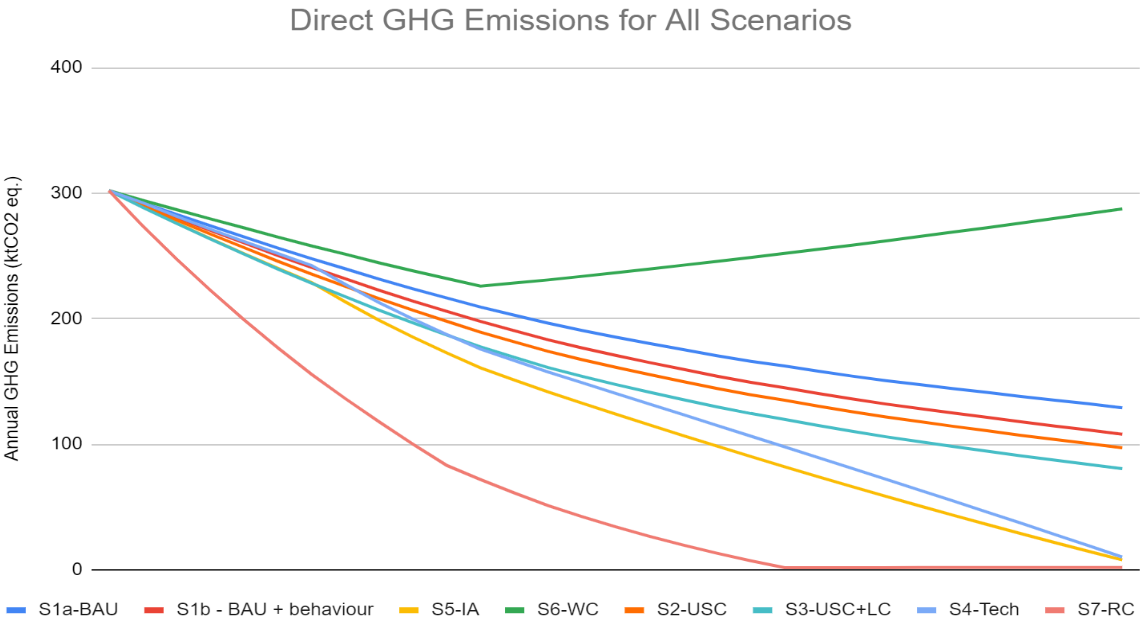


Figure 28: Direct annual GHG emissions for all scenarios during 2020-2050.

According to Figure 28, following the base case, it is possible to reduce annual direct GHG emissions by more than 50% until 2050, however, the aim of the City of Reykjavik to be carbon neutral by 2040 will not be achieved. This analysis illustrates the potential of three scenarios (Tech, Integrated Approach, and Radical Change) to cut the annual direct GHG emissions completely by 2050.

As discussed earlier, indirect emissions from transportation have sometimes been excluded from GHG emissions calculations. Thus, in order to have a more comprehensive understanding of the total GHG emissions (both direct (or tailpipe) emissions, as well as indirect (or life-cycle) emissions),

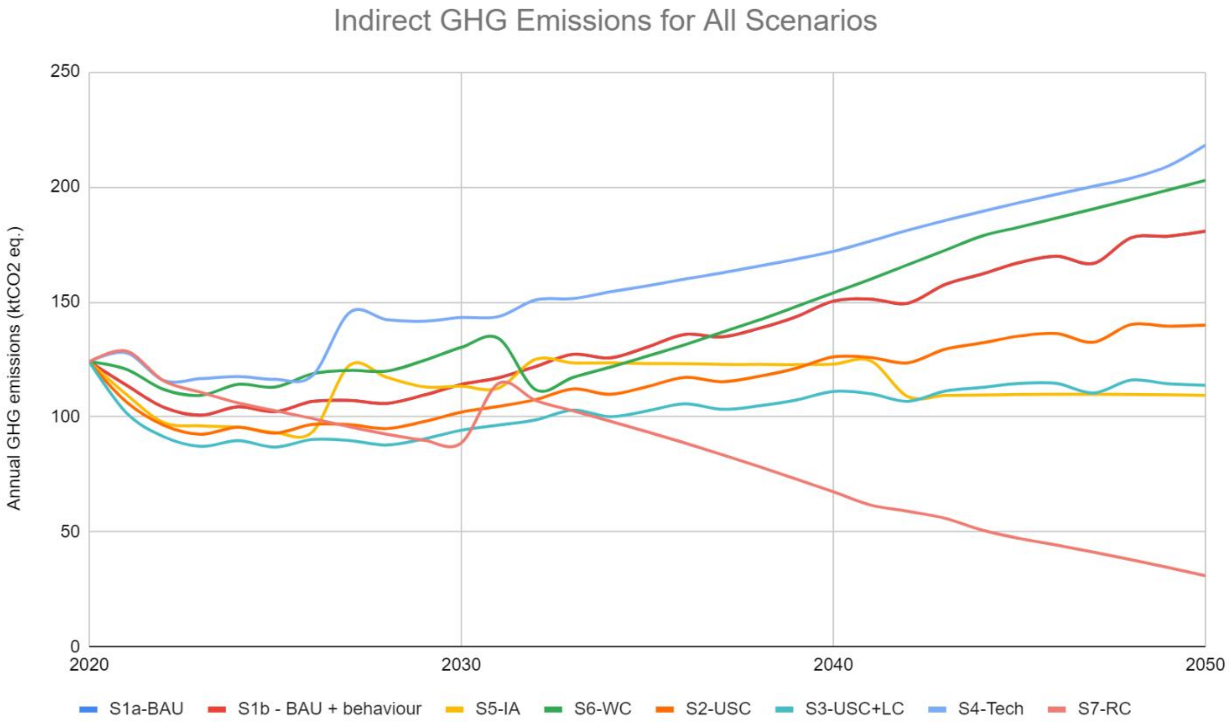


Figure 29: Indirect annual GHG emissions for all scenarios during 2020-2050.

Figure 29 shows the final indirect GHG emission estimates for 2050. These results show that by 2050 after all changes have been made, the Radical Change scenario will have the smallest output of annual emissions. It additionally shows however that urban structural change and technological changes will have similar results though for different reasons. In the S4 scenario the focus on urban form leads to higher modal shares of walking/biking and public transport, leading to both direct and indirect emissions. By 2050 for the S4-Tech, S5-Integrated approach and S7-Radical Change scenario however, investments have been made to completely electrify the transportation fleet, with the fastest transition being in the Radical Change scenario. The Tech scenario assumes still high vehicle ownership rates however, which leads to significantly higher fleet turnover and consequently higher indirect emissions. This tradeoff shows that when urban structural change and lifestyle changes are made, this will lead to a greater emission decrease than simply a full electrification of a vehicle fleet with no considerations towards vehicle ownership levels and urban form.

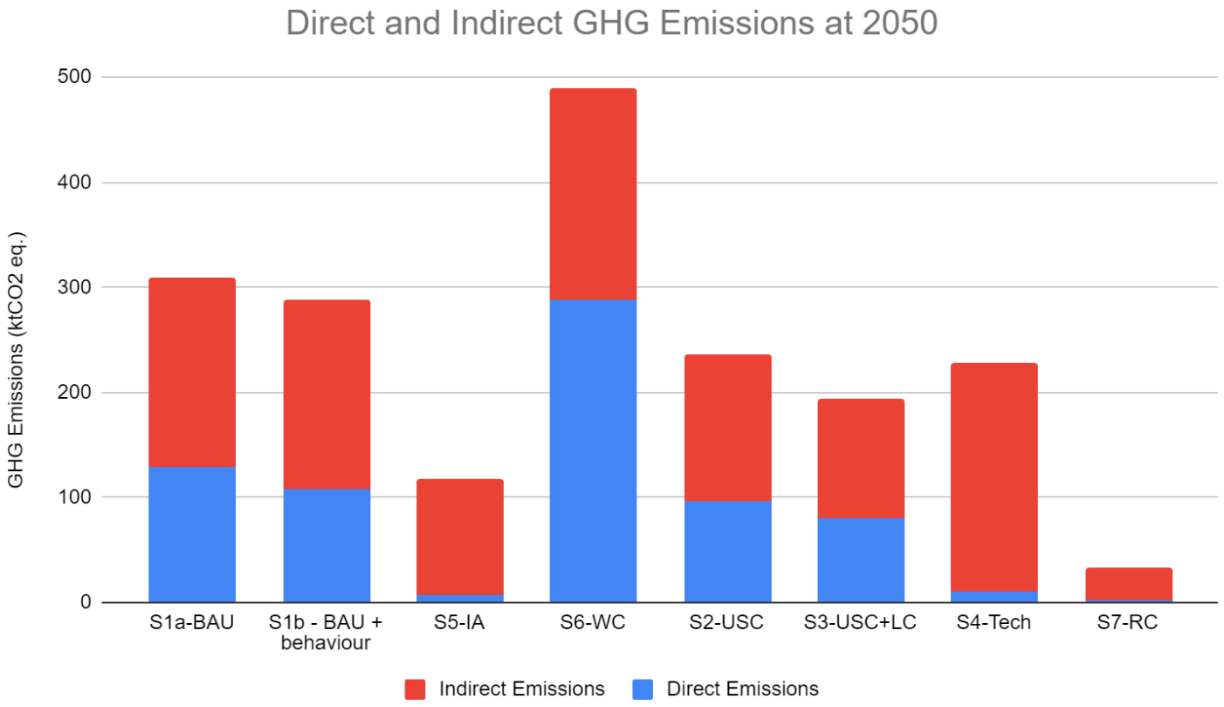


Figure 30: Direct and Indirect emissions for each scenario at 2050

Figure 31 shows how each scenario compares to the BAU case. This contrast between the direct and indirect emissions is again highlighted by the S4-Tech scenario, where indirect emissions are actually higher than the BAU case because of the higher BEV production requirements, but lower direct emissions due to the electrification of the vehicle fleet.

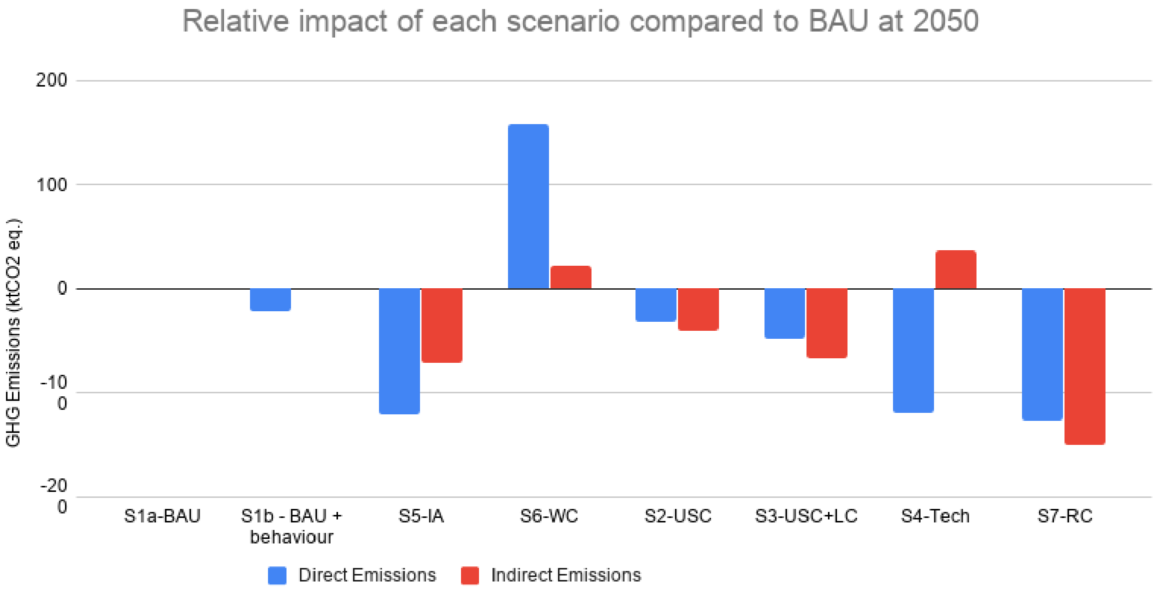


Figure 31: Relative direct and indirect emissions for each scenario at 2050 compared to S1-BAU scenario

The following section will first describe the results from the BAU scenario. The proceeding sections will then describe the results from each scenario and how they compare to the BAU scenario, and which primary factors of influence led to the greatest deviations from the BAU scenario. These factors of influence are the fundamental changes to the system analyzed within this report that lead to a change in GHG emissions and include the following: Travel demand, Modal shares, Technological changes, and Vehicle fleet size.

The change to travel demand is the change in emissions caused by an increase or decrease in the daily travel demand per capita estimated for Reykjavik. The modal share factor of influence is the impact changes in modal shares have on the final GHG results per scenario. The technological change includes the rate of transition to electric vehicles and impact of MaaS on the transportation system and associated annual GHG emissions. The vehicle fleet size influence factor measures the relative impact of a changing vehicle fleet size, including bus fleet and transportation service fleet.

S1a: Business As Usual

The BAU case which will act as the baseline for all future comparisons was defined by the current plans and projections by Icelandic authorities. This BAU case is defined by a continuation according to these plans, where it can be assumed that there will be some increases in the modal share of public transport and MaaS, but not significant increases. There is still progress towards the electrification of the vehicle fleet as is currently occurring. These three factors play a role in the decreasing emissions coming from the passenger vehicle fleet, primarily caused by the transition to electrification.

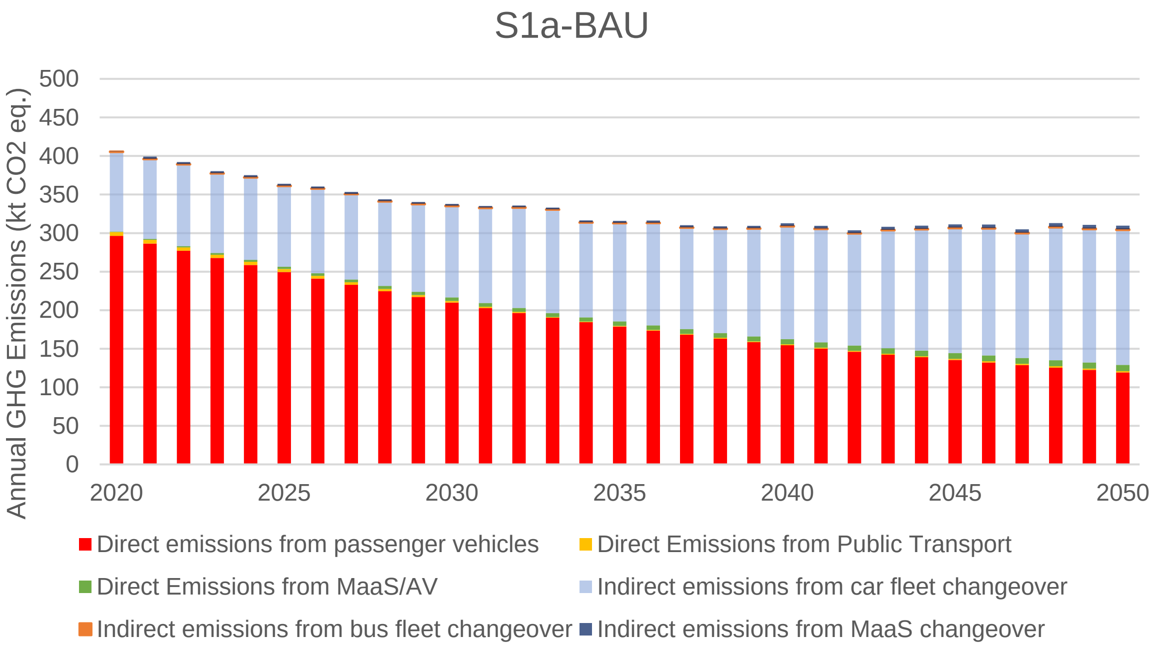


Figure 32: Relative direct and indirect emissions for each scenario at 2050 compared to S1-BAU scenario

S1b: Business As Usual + Behavioral Change

The S1b case follows the plans made by the city but implements them with an effort to change behavior. This behavioral change leads to a greater use of the public transportation system and more prominent share of citizens walking/biking. This leads to slightly lower annual emissions than the BAU case (Figure 33).

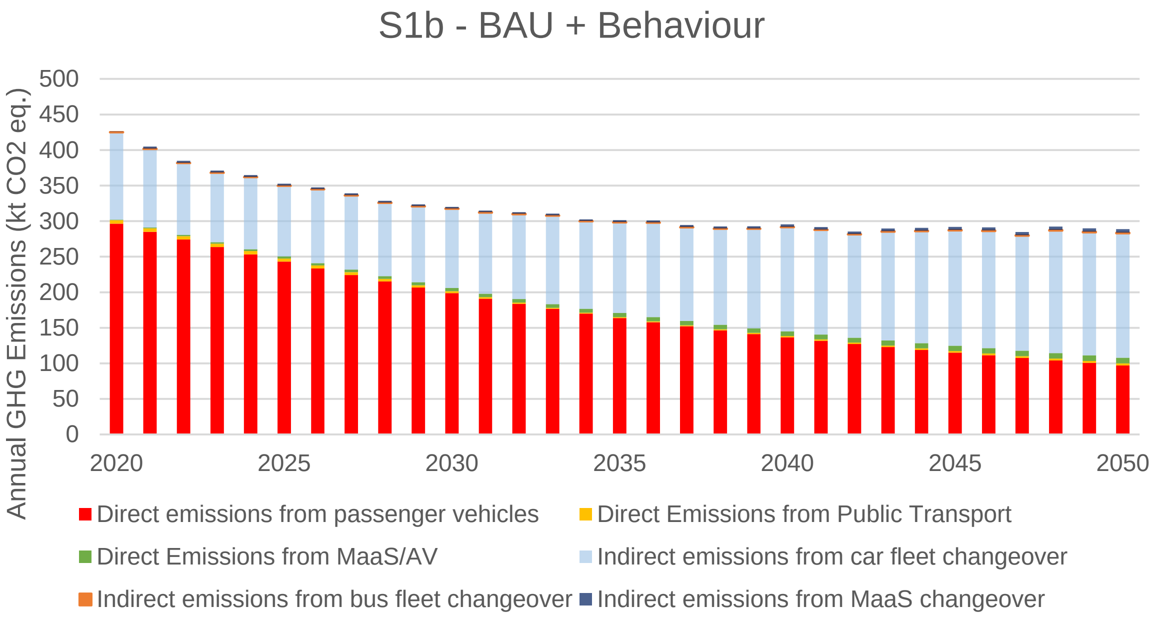


Figure 33: Direct and indirect emissions from different transport segments in S1b scenario

Figure 34 highlights that it is entirely modal share that causes this ~ 21 kt drop in GHG emissions by 2050, representing an approximate 6.5% drop in emissions from the BAU case.

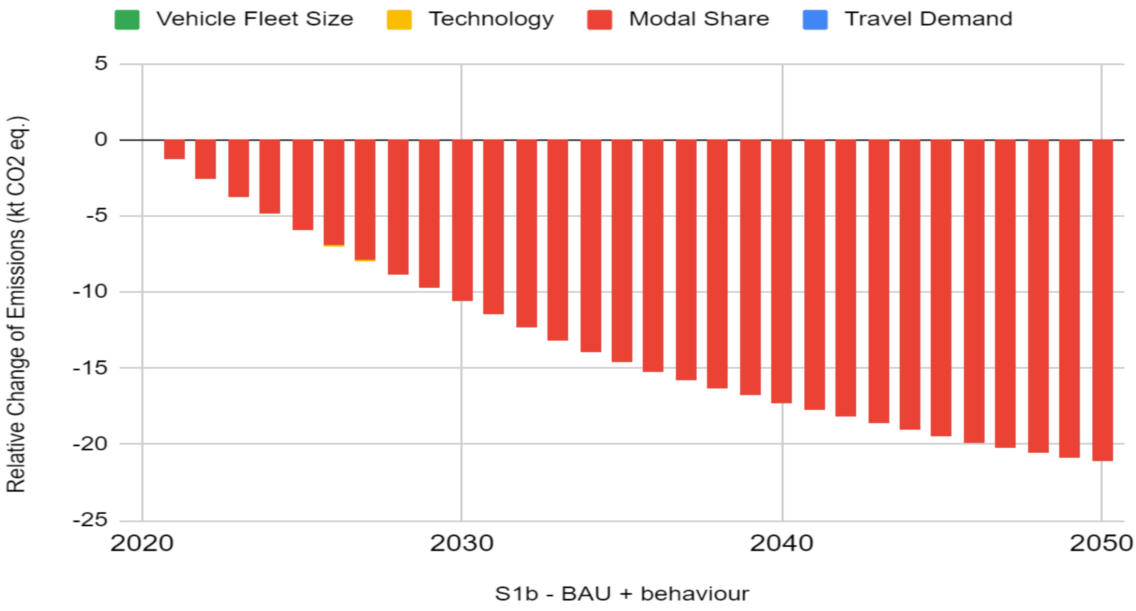


Figure 34: Contribution of each factor of influence in S1b compared to BAU

S2: Urban Structural Change

Figure 35 shows that this scenario which is focused on changes to urban structure can lead to significant emissions reductions. It can be seen that direct emissions decrease significantly and indirect emissions from fleet turnover is relatively controlled compared to the BAU scenario.

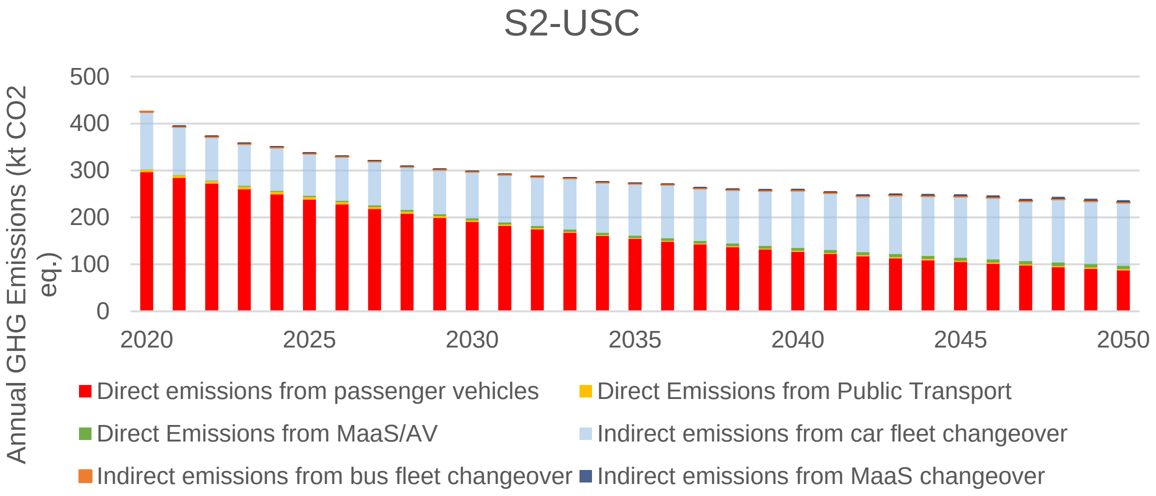


Figure 35: Direct and indirect emissions from different transport segments in USC scenario

Figure 36 illustrates the contribution of factors in reducing GHG emissions. Policies geared towards improving urban form, reducing the need for car ownership and promoting changes in the transportation modes played the largest role in decreasing the GHG emissions within this scenario. Change to urban structural form was estimated to reduce the annual GHG emissions in 2050 by 23.5%. Due to the change in modal shares caused by improved urban form and improved public transport, vehicle ownership was reduced, and this was responsible for 54% of the GHG reductions within this scenario % Change in modal shares itself through a greater amount of walking/cycling and use of public transportation led to more than 33% of the relative emission reductions by 2050.

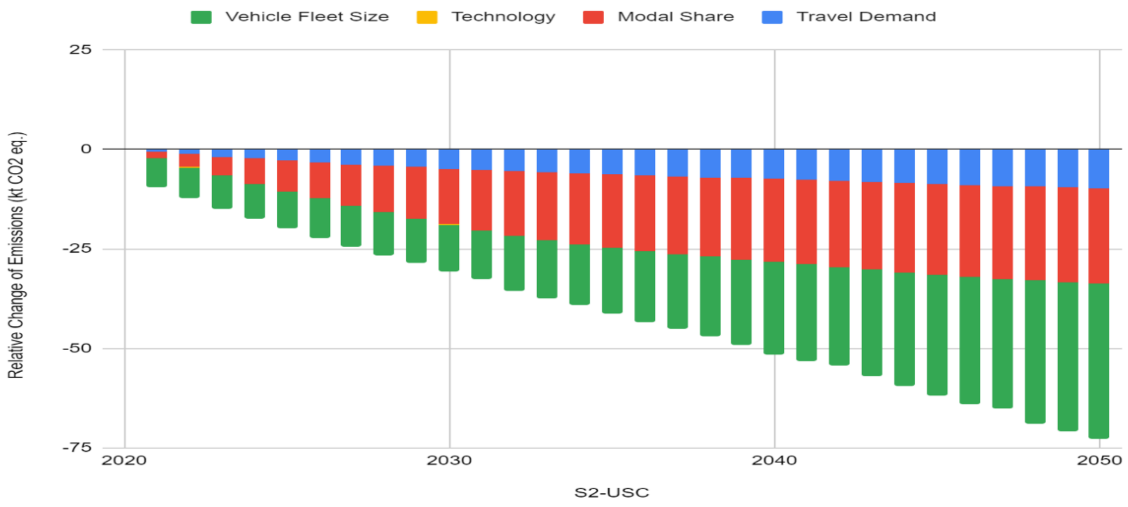


Figure 36: Contribution of each factor of influence in USC scenario compared to BAU

S3: Urban Structural Change + Lifestyle Change

Figure 37 reflects a similar trend as found in the S2 urban structural change scenario, but with the added effect of lifestyle change, where Reykjavik's population makes behavioral changes, further increasing the effectiveness of urban structural change policies. The S3 urban structural change with the addition of behavioral change results in 37% decrease in annual emissions in 2050 relative to the BAU scenario, a 13% addition from the S4 scenario.

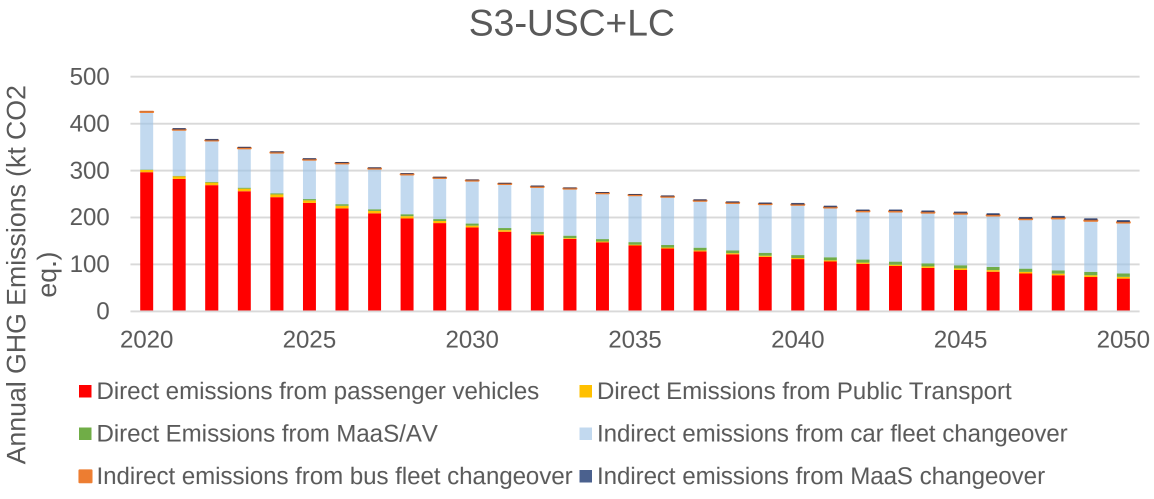


Figure 37: Direct and indirect emissions from different transport segments in USC+LC scenario

A similar pattern in the factors of influence can be seen in Figure 38 as in S3, but with a greater scale due to greater personal and public transport mode shares and an even further reduced vehicle ownership rates. Promoting a greater amount of walking/cycling and public transportation led to an almost 33% reduction of relative emission compared to the BAU case by 2050. Due to the change in modal shares and improved urban form and behavioral change in terms of vehicle ownership, an additional 54% decrease in GHG emissions was seen as compared to the BAU case and this again was the most important factor of influence during the entire study period.

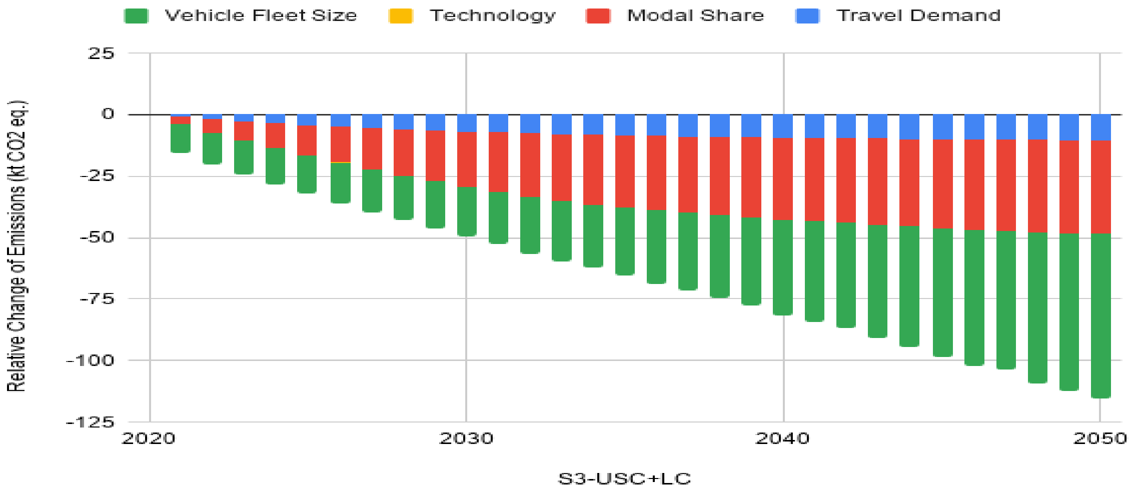


Figure 38: Contribution of each factor of influence in USC+LC scenario compared to BAU

S4: Technological Change

Figure 39 illustrates the direct and indirect emission profile of the S4 technological scenario. In this scenario, which is highly focused on the transition to e-mobility and MaaS, direct emissions were reduced to near zero by 2050, while the indirect emissions grew due to the need to produce a greater number of electric vehicles.

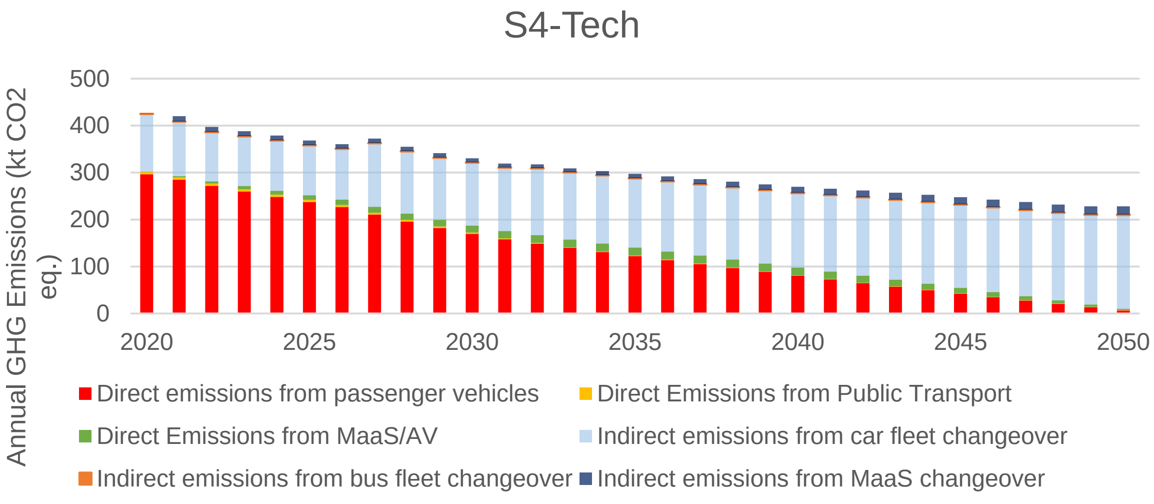


Figure 39: Direct and indirect emissions from different transport segments in Tech scenario

It can be seen in Figure 40 that this line of thinking holds true when analyzing the factors of influence, where technological improvements lead to significant reductions in emissions compared to the BAU case. However, due to the need for a greater amount of BEVs which are more emission intensive to produce, the emissions required to change over the vehicle fleet are greater than in the BAU scenario. While this tradeoff is more than offset by the improved reduction in direct emissions, it highlights the impact of indirect emissions which is often forgotten in transportation planning.

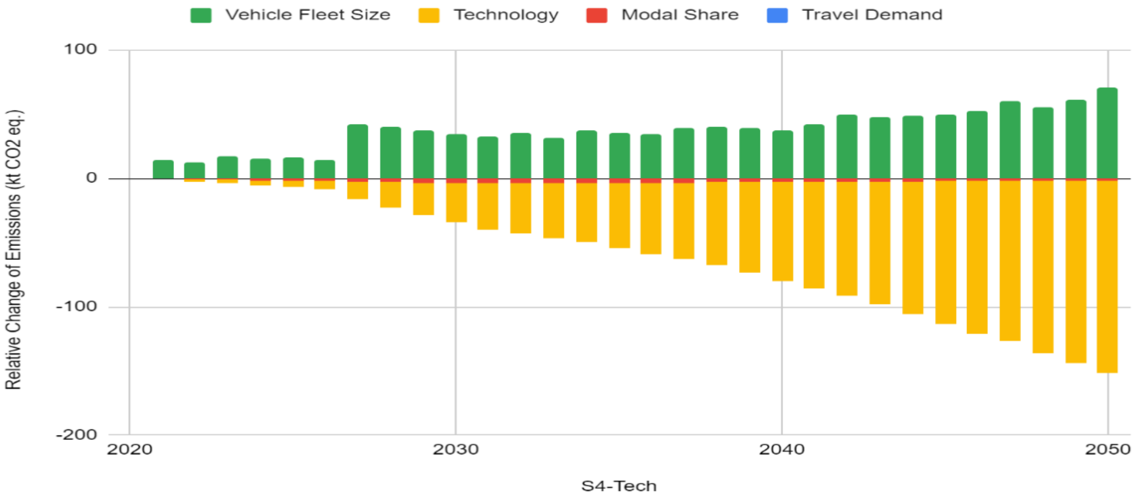


Figure 40: Contribution of each factor of influence in Tech scenario compared to BAU

S5: Integrated Approach Scenario

Figure 41 shows clearly that the Integrated Approach scenario leads to a significant drop in emissions, approaching near zero direct emissions by 2050. Indirect emissions from car fleet change over proves to be the most difficult emission category to reduce, because if a car fleet exists, there will always need to be a certain amount of turnover as cars approach their end of life.

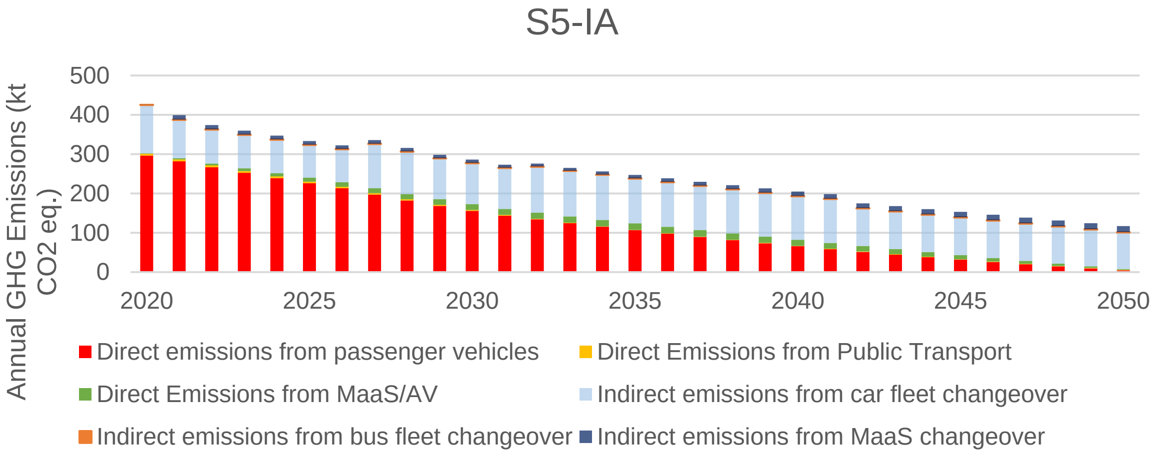


Figure 41: Direct and indirect emissions from different transport segments in the Integrated Approach scenario

Figure 42 illustrates the impact that each factor included within the Integrated Approach Scenario had on final GHG emissions as opposed to the BAU scenario. It can be seen that technological changes have the greatest impacts on final emissions reduction, leading to a 62% drop in total GHG emissions by 2050 compared to the BAU case. By 2050, technological changes of full transition to electric vehicles and influence of MaaS plays the largest role in decreasing the amount of emissions, responsible for ~78% of the decrease in emissions. The change in the vehicle fleet size shows large influence on final GHG emissions throughout the project time period, responsible for 21% of the GHG emission reductions, by 2050.

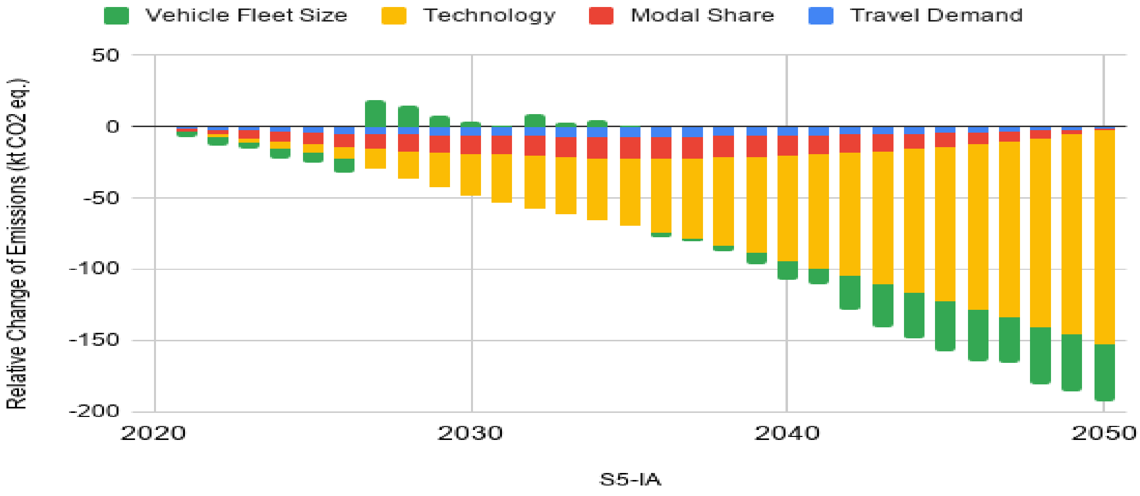


Figure 42: Contribution of each factor of influence in Integrated Approach scenario compared to BAU

S6: Worst Case Scenario

Figure 43 shows that the Worst-Case scenario is the scenario with the highest emissions, reflecting the scenario design of a movement away from any policies with the goal of reducing emissions from the transportation sector. It can be seen that the policies currently in place from the BAU scenario aid in stabilizing emissions until approximately 2030, at which point environmental planning and policies are abandoned, allowing emissions to continue increasing. The first emissions additionally grow as the demand for EV's stabilizes, leading to a large amount of both direct and indirect emissions.

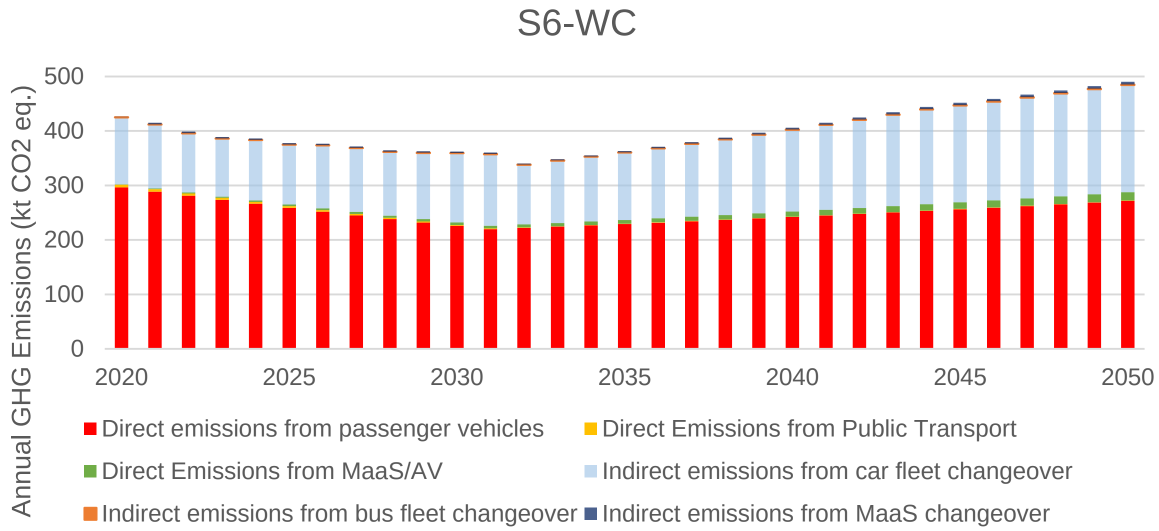


Figure 43: Direct and indirect emissions from different transport segments in Worst Case scenario

Figure 44 illustrates the impact of each factor had on final GHG emissions reductions compared to BAU scenario. It can be seen that the shift away from electric vehicles leads to the largest increase in final GHG emissions by 2050, which highlights the need to improve the vehicle fleet technology.

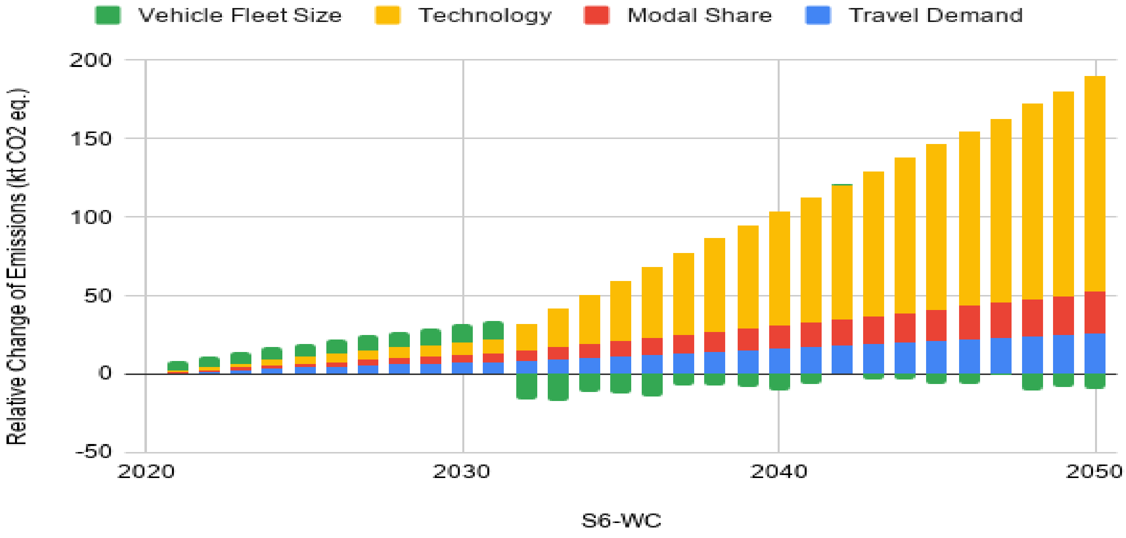


Figure 44: Contribution of each factor of influence in Worst Case scenario compared to BAU

S7. Radical Change Scenario

Figure 45 illustrates the direct and indirect emission profile of the S7 Radical Change scenario. The radical change scenario was designed to illustrate a radical shift in society, led by rapid electrification of transport, significantly improved urban form, and high use of transportation services such as MaaS and public transport. The high level of integration of these policies within this proposed scenario lead to a nearly 90% reduction of GHG emissions by 2050 as compared to the BAU scenario.

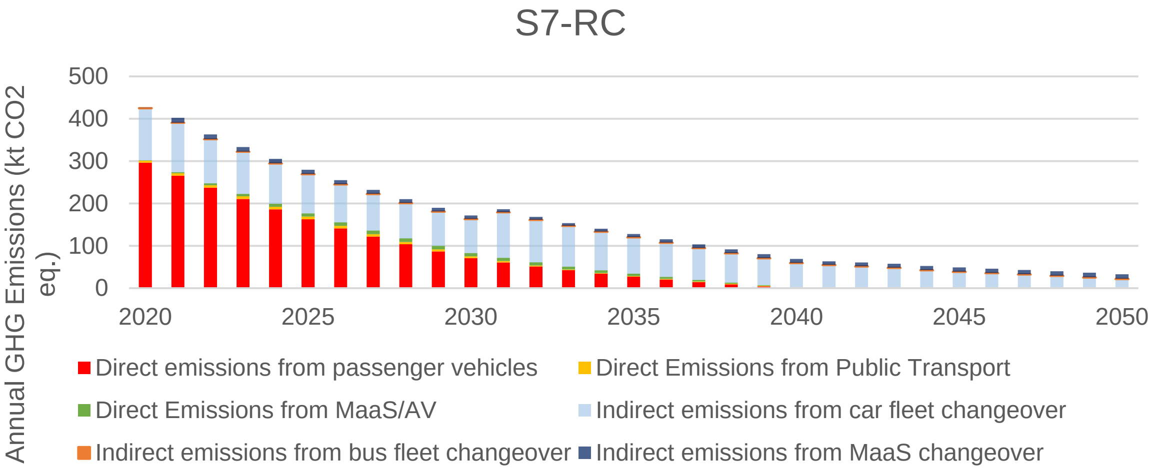


Figure 45: Direct and indirect emissions from different transport segments in the Radical Change scenario

Figure 46 shows that the rapid electrification of the vehicle fleet, combined with controlling the vehicle fleet size (driven by supporting MaaS and public transit) played the largest roles in reducing emissions, accounting for 57% and 43% of the emissions reductions by 2050, respectively. Unlike in the S6-Tech scenario where the indirect emissions counter-balance the benefit of fleet electrification, due to the reduction in vehicle ownership, the vehicle fleet turnover indirect emissions are reduced, leading to significant GHG reductions within this Radical Change Scenario.

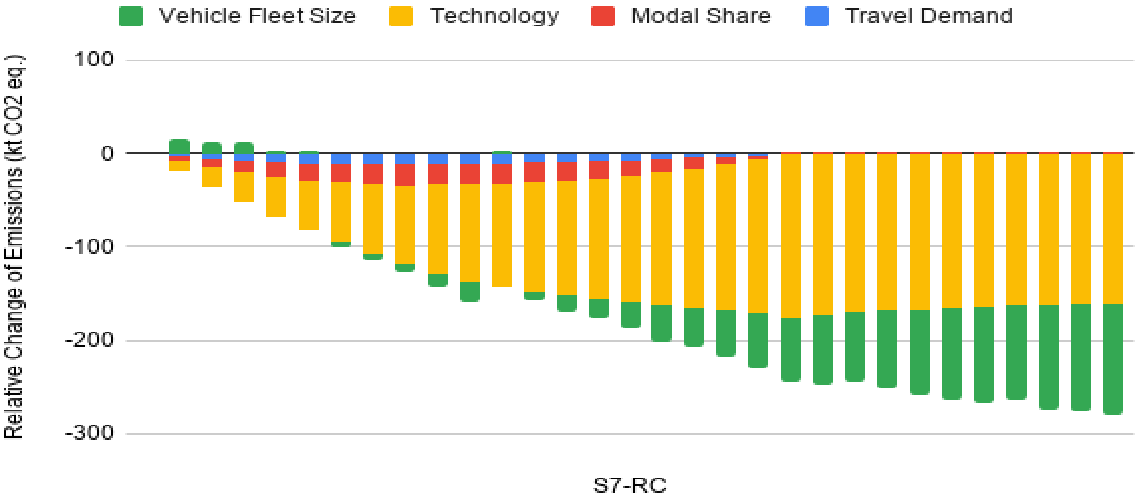


Figure 46: Contribution of each factor of influence in the radical change scenario compared to BAU

Interpretation of Results

The results of this study show that the most effective GHG emission reduction strategy would incorporate a four-pronged strategy with the goals of accelerating the transition to e-mobility, improving urban structural form to promote greater use of public transportation and walking/cycling, encouraging behavioral change to enhance the impacts of this improved urban form, and policy instruments to support each of these changes. This integrated strategy is best shown in the S5-Intgreated Approach scenario where the improvements made in the other scenarios were combined to develop a societal form which encourages densification and carbon-free transportation such as walking and cycling. When needed an efficient public transport and MaaS service exists, and car ownership is seen as a luxury as opposed to a necessity.

Disaggregating this four-pronged approach, the results showed a difference in magnitude in terms of which strategy was most effective and displayed different advantages and disadvantages. Technological changes led to the most significant reductions in final GHG emissions, though the rebound effect of greater indirect emissions due to the need to manufacture EVs makes urban structural and behavioral changes both relevant and important. The supporting policy instruments were seen as the promoting force for each of these changes.

The technological scenario saw the advantages of a full transition to e-mobility in terms of direct GHG emission reductions however, which led to near zero direct GHG emissions by 2050, making it a comparably effective policy with urban structural change. The indirect emissions associated with car fleet turnover was the major disadvantage of the technological scenario, where vehicle ownership was still considered a necessity due to lacking improvements in urban form, and due to BEVs' higher production emissions, this led to higher indirect GHG emissions.

Urban structural change saw the greatest decrease in direct emissions through greater use of personal (walking/cycling) and public transport. Due to slower technological improvement rates however, the direct emissions remained higher than if there were a full transition to EVs. This improvement in modal shares however also led to reduction in car ownership which decreases the indirect emissions associated with car fleet turnover.

Lifestyle change showed the smallest impact of the three primary strategies, where in S1b and S5, the addition of lifestyle changes while making a noticeable impact, typically only led to an approximate 5-10% reduction in GHG emissions as compared to the BAU scenario. While this may appear to make the lifestyle change driver less attractive, it is important to remember that improved urban form and the transition to e-mobility will require significant infrastructural changes and investments. Meanwhile, lifestyle changes can be encouraged right now at significantly lower costs compared to the other two drivers and can be used to enhance the other two drivers.

A radical integrated approach of all of these factors would be the best approach in reducing GHG emissions from the transportation sector, shown in both the S5-Integrated Approach and even more heavily in the S7-Radical Change scenario.

Conclusions

So far, there is only limited knowledge of current GHG emissions of passenger transportation in the Greater Reykjavik area and particularly of the potential future development pathways. Besides, while the electric vehicle can be seen as a prominent solution to cut the direct (or tailpipe) GHG emissions, there is a lack of understanding of the indirect (or life-cycle) GHG emissions from electric vehicles and other solutions such as MaaS over the lifetime of light-duty vehicles. Moreover, the emissions from the transport sector depend on the simultaneous development in travel behaviors and technologies, and both of these depend on the steering policies, incentives and disincentives, and on several geographical and urban structural factors.

In this project we created a set of different development scenarios for 2020-2050 for the Reykjavik Capital Region and analyzed the annual and cumulative emissions development in each, and their division between local direct and global indirect components. First, we identified four key drivers that will determine how the passenger transport in Reykjavik Capital Region might look in 2050. These four drivers include, urban structure, lifestyle, technologies and policies and regulation. We then defined seven scenarios of future changes in passenger transport in Reykjavik Capital Region, based on a comprehensive review of policy documents in the region and academic literature that describes main factors of change and policy instruments that influence travel behavior. The policy documents form the basis of the BAU scenario against which the different alternative development scenarios were compared. An analytical framework linking all the different components together was developed to assess direct and indirect GHG emissions for each scenario

The results show that it is possible to reduce direct annual GHG emissions by more than 50% until 2050, however, the aim of the City of Reykjavik to be carbon neutral by 2040 will not be achieved. This analysis illustrates the potential of three scenarios (Tech, Integrated Approach, and Radical Change) to cut the direct GHG emissions completely by 2050. On the other hand, the indirect GHG emissions will significantly increase for most of the scenarios. As expected, changes in the urban structural change and behavior combined with the policies toward electrification have the potential to cut the overall emissions by 60-90% by 2050, depending on the intensity of the changes.

We also compared the contribution of four primary factors of influence (Travel demand, Modal shares, Technological changes, and Vehicle fleet size) in reducing the GHG emissions for all scenarios. In the Integrated Approach scenario, it was concluded that technological development was the main contributor (78%) followed by the reduction in vehicle fleet size (21%). In scenario 2, focusing on the urban structural change, the main contributor is the change in vehicle fleet size (54%), followed by the change in modal share (33%),

This analysis provides the pioneering perspective on the potential impacts of key drivers, including urban structure, lifestyle, technologies and policies and regulation on both direct and indirect emissions from passenger transport in Reykjavik region. It was concluded that by implementing multiple supportive policies (VAT exemption for electric vehicles as well as imposing a ban on the new sales of ICE and HEV from 2025), we can expect a shift to electric powertrain for both passenger vehicles and bus fleets which can significantly reduce direct emissions. However, in order to mitigate indirect emissions, it’s necessary to combine those policies with plans to increase urban density in the region and induce changes in travel behavior (such as high-occupancy vehicle lanes).

While the outcomes of the different scenarios included in this analysis are highly uncertain due to so many uncertain developments affecting any such long-term future predictions, the utility of this analysis is still high. The different scenarios show the potentials embedded in the different key development components and provide baseline values for deeper and more detailed analyses on different alternative options. The inclusion of the global indirect production and delivery chain emissions give insight on the overall global GHG impacts, a perspective often missing from transport sector GHG analyses. Moreover, according to the results of this study, without significant and rapid technological development reducing the indirect emissions, rapid decarbonization of passenger transport is impossible without major behavioral changes.

Acknowledgments

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Appendix A

Vehicle Fleet Composition per Scenario

S1b - BAU + behavior

	ICE_gasoline	HEV_gasoline	PHEV_gasoline	ICE_diesel	HEV_diesel	PHEV_diesel	BEV
2019	57.3%	3.2%	3.0%	31.1%	2.3%	1.5%	1.6%
2020	53.2%	4.1%	3.9%	31.0%	3.2%	2.3%	2.3%
2021	50.3%	4.9%	4.8%	29.8%	4.0%	3.0%	3.2%
2022	47.6%	5.5%	5.6%	28.6%	4.7%	3.6%	4.3%
2023	45.0%	6.0%	6.4%	27.4%	5.3%	4.3%	5.6%
2024	42.5%	6.4%	7.1%	26.2%	5.8%	4.9%	7.0%
2025	40.1%	6.8%	7.8%	25.1%	6.2%	5.4%	8.6%
2026	37.9%	7.1%	8.4%	24.0%	6.6%	5.9%	10.2%
2027	35.8%	7.3%	8.9%	22.9%	6.9%	6.3%	11.9%
2028	33.8%	7.5%	9.4%	21.9%	7.2%	6.7%	13.5%
2029	32.0%	7.7%	9.8%	20.9%	7.4%	7.1%	15.1%
2030	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2031	28.6%	7.9%	10.5%	19.2%	7.8%	7.8%	18.2%
2032	27.0%	8.0%	10.9%	18.4%	8.0%	8.1%	19.7%
2033	25.6%	8.1%	11.2%	17.6%	8.1%	8.3%	21.1%
2034	24.2%	8.1%	11.5%	16.9%	8.3%	8.6%	22.4%
2035	22.9%	8.2%	11.7%	16.2%	8.4%	8.9%	23.8%
2036	21.7%	8.2%	12.0%	15.5%	8.5%	9.1%	25.0%
2037	20.5%	8.2%	12.2%	14.9%	8.5%	9.3%	26.3%
2038	19.4%	8.2%	12.4%	14.3%	8.6%	9.5%	27.5%
2039	18.4%	8.2%	12.6%	13.8%	8.7%	9.7%	28.7%
2040	17.4%	8.2%	12.8%	13.2%	8.7%	9.9%	29.9%
2041	16.5%	8.1%	12.9%	12.7%	8.7%	10.0%	31.0%
2042	15.6%	8.1%	13.0%	12.2%	8.7%	10.2%	32.1%
2043	14.8%	8.0%	13.2%	11.8%	8.7%	10.3%	33.2%
2044	14.0%	8.0%	13.3%	11.3%	8.7%	10.5%	34.3%

2045	13.3%	7.9%	13.4%	10.9%	8.7%	10.6%	35.4%
2046	12.6%	7.8%	13.4%	10.5%	8.6%	10.7%	36.4%
2047	11.9%	7.7%	13.5%	10.1%	8.6%	10.8%	37.5%
2048	11.3%	7.6%	13.6%	9.7%	8.5%	10.9%	38.5%
2049	10.7%	7.4%	13.6%	9.3%	8.4%	11.0%	39.6%
2050	10.1%	7.3%	13.6%	9.0%	8.4%	11.0%	40.6%

S1a - BAU

	ICE_gasoline	**HEV_gasoline**	**PHEV_gasoline**	**ICE_diesel**	**HEV_diesel**	**PHEV_diesel**	**BEV**
2019	57.3%	3.2%	3.0%	31.1%	2.3%	1.5%	1.6%
2020	53.2%	4.1%	3.9%	31.0%	3.2%	2.3%	2.3%
2021	50.3%	4.9%	4.8%	29.8%	4.0%	3.0%	3.2%
2022	47.6%	5.5%	5.6%	28.6%	4.7%	3.6%	4.3%
2023	45.0%	6.0%	6.4%	27.4%	5.3%	4.3%	5.6%
2024	42.5%	6.4%	7.1%	26.2%	5.8%	4.9%	7.0%
2025	40.1%	6.8%	7.8%	25.1%	6.2%	5.4%	8.6%
2026	37.9%	7.1%	8.4%	24.0%	6.6%	5.9%	10.2%
2027	35.8%	7.3%	8.9%	22.9%	6.9%	6.3%	11.9%
2028	33.8%	7.5%	9.4%	21.9%	7.2%	6.7%	13.5%
2029	32.0%	7.7%	9.8%	20.9%	7.4%	7.1%	15.1%
2030	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2031	28.6%	7.9%	10.5%	19.2%	7.8%	7.8%	18.2%
2032	27.0%	8.0%	10.9%	18.4%	8.0%	8.1%	19.7%
2033	25.6%	8.1%	11.2%	17.6%	8.1%	8.3%	21.1%
2034	24.2%	8.1%	11.5%	16.9%	8.3%	8.6%	22.4%
2035	22.9%	8.2%	11.7%	16.2%	8.4%	8.9%	23.8%
2036	21.7%	8.2%	12.0%	15.5%	8.5%	9.1%	25.0%
2037	20.5%	8.2%	12.2%	14.9%	8.5%	9.3%	26.3%
2038	19.4%	8.2%	12.4%	14.3%	8.6%	9.5%	27.5%
2039	18.4%	8.2%	12.6%	13.8%	8.7%	9.7%	28.7%
2040	17.4%	8.2%	12.8%	13.2%	8.7%	9.9%	29.9%

2041	16.5%	8.1%	12.9%	12.7%	8.7%	10.0%	31.0%
2042	15.6%	8.1%	13.0%	12.2%	8.7%	10.2%	32.1%
2043	14.8%	8.0%	13.2%	11.8%	8.7%	10.3%	33.2%
2044	14.0%	8.0%	13.3%	11.3%	8.7%	10.5%	34.3%
2045	13.3%	7.9%	13.4%	10.9%	8.7%	10.6%	35.4%
2046	12.6%	7.8%	13.4%	10.5%	8.6%	10.7%	36.4%
2047	11.9%	7.7%	13.5%	10.1%	8.6%	10.8%	37.5%
2048	11.3%	7.6%	13.6%	9.7%	8.5%	10.9%	38.5%
2049	10.7%	7.4%	13.6%	9.3%	8.4%	11.0%	39.6%
2050	10.1%	7.3%	13.6%	9.0%	8.4%	11.0%	40.6%

S2-USC

	ICE_gasoline	**HEV_gasoline**	**PHEV_gasoline**	**ICE_diesel**	**HEV_diesel**	**PHEV_diesel**	**BEV**
2019	57.3%	3.2%	3.0%	31.1%	2.3%	1.5%	1.6%
2020	53.2%	4.1%	3.9%	31.0%	3.2%	2.3%	2.3%
2021	50.3%	4.9%	4.8%	29.8%	4.0%	3.0%	3.2%
2022	47.6%	5.5%	5.6%	28.6%	4.7%	3.6%	4.3%
2023	45.0%	6.0%	6.4%	27.4%	5.3%	4.3%	5.6%
2024	42.5%	6.4%	7.1%	26.2%	5.8%	4.9%	7.0%
2025	40.1%	6.8%	7.8%	25.1%	6.2%	5.4%	8.6%
2026	37.9%	7.1%	8.4%	24.0%	6.6%	5.9%	10.2%
2027	35.8%	7.3%	8.9%	22.9%	6.9%	6.3%	11.9%
2028	33.8%	7.5%	9.4%	21.9%	7.2%	6.7%	13.5%
2029	32.0%	7.7%	9.8%	20.9%	7.4%	7.1%	15.1%
2030	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2031	28.6%	7.9%	10.5%	19.2%	7.8%	7.8%	18.2%
2032	27.0%	8.0%	10.9%	18.4%	8.0%	8.1%	19.7%

2033	25.6%	8.1%	11.2%	17.6%	8.1%	8.3%	21.1%
2034	24.2%	8.1%	11.5%	16.9%	8.3%	8.6%	22.4%
2035	22.9%	8.2%	11.7%	16.2%	8.4%	8.9%	23.8%
2036	21.7%	8.2%	12.0%	15.5%	8.5%	9.1%	25.0%
2037	20.5%	8.2%	12.2%	14.9%	8.5%	9.3%	26.3%
2038	19.4%	8.2%	12.4%	14.3%	8.6%	9.5%	27.5%
2039	18.4%	8.2%	12.6%	13.8%	8.7%	9.7%	28.7%
2040	17.4%	8.2%	12.8%	13.2%	8.7%	9.9%	29.9%
2041	16.5%	8.1%	12.9%	12.7%	8.7%	10.0%	31.0%
2042	15.6%	8.1%	13.0%	12.2%	8.7%	10.2%	32.1%
2043	14.8%	8.0%	13.2%	11.8%	8.7%	10.3%	33.2%
2044	14.0%	8.0%	13.3%	11.3%	8.7%	10.5%	34.3%
2045	13.3%	7.9%	13.4%	10.9%	8.7%	10.6%	35.4%
2046	12.6%	7.8%	13.4%	10.5%	8.6%	10.7%	36.4%
2047	11.9%	7.7%	13.5%	10.1%	8.6%	10.8%	37.5%
2048	11.3%	7.6%	13.6%	9.7%	8.5%	10.9%	38.5%
2049	10.7%	7.4%	13.6%	9.3%	8.4%	11.0%	39.6%
2050	10.1%	7.3%	13.6%	9.0%	8.4%	11.0%	40.6%

S3-USC+LC

	ICE_gasoline	**HEV_gasoline**	**PHEV_gasoline**	**ICE_diesel**	**HEV_diesel**	**PHEV_diesel**	**BEV**
2019	57.3%	3.2%	3.0%	31.1%	2.3%	1.5%	1.6%
2020	53.2%	4.1%	3.9%	31.0%	3.2%	2.3%	2.3%
2021	50.3%	4.9%	4.8%	29.8%	4.0%	3.0%	3.2%
2022	47.6%	5.5%	5.6%	28.6%	4.7%	3.6%	4.3%
2023	45.0%	6.0%	6.4%	27.4%	5.3%	4.3%	5.6%
2024	42.5%	6.4%	7.1%	26.2%	5.8%	4.9%	7.0%
2025	40.1%	6.8%	7.8%	25.1%	6.2%	5.4%	8.6%
2026	37.9%	7.1%	8.4%	24.0%	6.6%	5.9%	10.2%
2027	35.8%	7.3%	8.9%	22.9%	6.9%	6.3%	11.9%
2028	33.8%	7.5%	9.4%	21.9%	7.2%	6.7%	13.5%

2029	32.0%	7.7%	9.8%	20.9%	7.4%	7.1%	15.1%
2030	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2031	28.6%	7.9%	10.5%	19.2%	7.8%	7.8%	18.2%
2032	27.0%	8.0%	10.9%	18.4%	8.0%	8.1%	19.7%
2033	25.6%	8.1%	11.2%	17.6%	8.1%	8.3%	21.1%
2034	24.2%	8.1%	11.5%	16.9%	8.3%	8.6%	22.4%
2035	22.9%	8.2%	11.7%	16.2%	8.4%	8.9%	23.8%
2036	21.7%	8.2%	12.0%	15.5%	8.5%	9.1%	25.0%
2037	20.5%	8.2%	12.2%	14.9%	8.5%	9.3%	26.3%
2038	19.4%	8.2%	12.4%	14.3%	8.6%	9.5%	27.5%
2039	18.4%	8.2%	12.6%	13.8%	8.7%	9.7%	28.7%
2040	17.4%	8.2%	12.8%	13.2%	8.7%	9.9%	29.9%
2041	16.5%	8.1%	12.9%	12.7%	8.7%	10.0%	31.0%
2042	15.6%	8.1%	13.0%	12.2%	8.7%	10.2%	32.1%
2043	14.8%	8.0%	13.2%	11.8%	8.7%	10.3%	33.2%
2044	14.0%	8.0%	13.3%	11.3%	8.7%	10.5%	34.3%
2045	13.3%	7.9%	13.4%	10.9%	8.7%	10.6%	35.4%
2046	12.6%	7.8%	13.4%	10.5%	8.6%	10.7%	36.4%
2047	11.9%	7.7%	13.5%	10.1%	8.6%	10.8%	37.5%
2048	11.3%	7.6%	13.6%	9.7%	8.5%	10.9%	38.5%
2049	10.7%	7.4%	13.6%	9.3%	8.4%	11.0%	39.6%
2050	10.1%	7.3%	13.6%	9.0%	8.4%	11.0%	40.6%

S4-Tech

	ICE_gasoline	HEV_gasoline	PHEV_gasoline	ICE_diesel	HEV_diesel	PHEV_diesel	BEV
2019	57.3%	3.2%	3.0%	31.1%	2.3%	1.5%	1.6%
2020	53.5%	4.1%	3.9%	31.0%	3.2%	2.2%	2.2%

2021	50.6%	4.7%	4.8%	29.7%	3.9%	3.0%	3.2%
2022	47.8%	5.3%	5.7%	28.5%	4.5%	3.7%	4.4%
2023	45.2%	5.7%	6.7%	27.3%	4.9%	4.5%	5.7%
2024	42.8%	6.1%	7.4%	26.1%	5.3%	5.1%	7.2%
2025	40.4%	6.4%	8.1%	24.9%	5.7%	5.7%	8.8%
2026	37.4%	5.9%	9.5%	23.1%	5.2%	6.8%	12.1%
2027	34.6%	5.4%	10.8%	21.3%	4.8%	7.8%	15.2%
2028	32.0%	5.0%	11.8%	19.8%	4.5%	8.6%	18.3%
2029	29.6%	4.7%	12.8%	18.3%	4.1%	9.4%	21.1%
2030	27.4%	4.3%	13.6%	16.9%	3.8%	10.1%	23.8%
2031	26.0%	4.1%	12.9%	16.1%	3.6%	9.6%	27.7%
2032	24.7%	3.9%	12.2%	15.2%	3.4%	9.1%	31.5%
2033	23.3%	3.7%	11.6%	14.4%	3.2%	8.6%	35.3%
2034	21.9%	3.4%	10.9%	13.5%	3.0%	8.1%	39.1%
2035	20.6%	3.2%	10.2%	12.7%	2.9%	7.6%	42.9%
2036	19.2%	3.0%	9.5%	11.8%	2.7%	7.1%	46.7%
2037	17.8%	2.8%	8.8%	11.0%	2.5%	6.6%	50.5%
2038	16.4%	2.6%	8.2%	10.1%	2.3%	6.1%	54.3%
2039	15.1%	2.4%	7.5%	9.3%	2.1%	5.6%	58.1%
2040	13.7%	2.2%	6.8%	8.5%	1.9%	5.1%	62.0%
2041	12.3%	1.9%	6.1%	7.6%	1.7%	4.5%	65.8%
2042	11.0%	1.7%	5.4%	6.8%	1.5%	4.0%	69.6%
2043	9.6%	1.5%	4.8%	5.9%	1.3%	3.5%	73.4%
2044	8.2%	1.3%	4.1%	5.1%	1.1%	3.0%	77.2%
2045	6.9%	1.1%	3.4%	4.2%	1.0%	2.5%	81.0%
2046	5.5%	0.9%	2.7%	3.4%	0.8%	2.0%	84.8%
2047	4.1%	0.6%	2.0%	2.5%	0.6%	1.5%	88.6%
2048	2.7%	0.4%	1.4%	1.7%	0.4%	1.0%	92.4%
2049	1.4%	0.2%	0.7%	0.8%	0.2%	0.5%	96.2%
2050	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%

S5-IA

	ICE_gasoli	**HEV_gasol**	**PHEV_gas**	**ICE_diesel**	**HEV_diese**	**PHEV_die**	**BEV**

	ne	**ine**	**oline**		**l**	**sel**	
2019	57.3%	3.2%	3.0%	31.1%	2.3%	1.5%	1.6%
2020	53.5%	4.1%	3.9%	31.0%	3.2%	2.2%	2.2%
2021	50.6%	4.7%	4.8%	29.7%	3.9%	3.0%	3.2%
2022	47.8%	5.3%	5.7%	28.5%	4.5%	3.7%	4.4%
2023	45.2%	5.7%	6.7%	27.3%	4.9%	4.5%	5.7%
2024	42.8%	6.1%	7.4%	26.1%	5.3%	5.1%	7.2%
2025	40.4%	6.4%	8.1%	24.9%	5.7%	5.7%	8.8%
2026	37.4%	5.9%	9.5%	23.1%	5.2%	6.8%	12.1%
2027	34.6%	5.4%	10.8%	21.3%	4.8%	7.8%	15.2%
2028	32.0%	5.0%	11.8%	19.8%	4.5%	8.6%	18.3%
2029	29.6%	4.7%	12.8%	18.3%	4.1%	9.4%	21.1%
2030	27.4%	4.3%	13.6%	16.9%	3.8%	10.1%	23.8%
2031	26.0%	4.1%	12.9%	16.1%	3.6%	9.6%	27.7%
2032	24.7%	3.9%	12.2%	15.2%	3.4%	9.1%	31.5%
2033	23.3%	3.7%	11.6%	14.4%	3.2%	8.6%	35.3%
2034	21.9%	3.4%	10.9%	13.5%	3.0%	8.1%	39.1%
2035	20.6%	3.2%	10.2%	12.7%	2.9%	7.6%	42.9%
2036	19.2%	3.0%	9.5%	11.8%	2.7%	7.1%	46.7%
2037	17.8%	2.8%	8.8%	11.0%	2.5%	6.6%	50.5%
2038	16.4%	2.6%	8.2%	10.1%	2.3%	6.1%	54.3%
2039	15.1%	2.4%	7.5%	9.3%	2.1%	5.6%	58.1%

2040	13.7%	2.2%	6.8%	8.5%	1.9%	5.1%	62.0%
2041	12.3%	1.9%	6.1%	7.6%	1.7%	4.5%	65.8%
2042	11.0%	1.7%	5.4%	6.8%	1.5%	4.0%	69.6%
2043	9.6%	1.5%	4.8%	5.9%	1.3%	3.5%	73.4%
2044	8.2%	1.3%	4.1%	5.1%	1.1%	3.0%	77.2%
2045	6.9%	1.1%	3.4%	4.2%	1.0%	2.5%	81.0%
2046	5.5%	0.9%	2.7%	3.4%	0.8%	2.0%	84.8%
2047	4.1%	0.6%	2.0%	2.5%	0.6%	1.5%	88.6%
2048	2.7%	0.4%	1.4%	1.7%	0.4%	1.0%	92.4%
2049	1.4%	0.2%	0.7%	0.8%	0.2%	0.5%	96.2%
2050	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%

S6-WC

	ICE_gasoline	**HEV_gasoline**	**PHEV_gasoline**	**ICE_diesel**	**HEV_diesel**	**PHEV_diesel**	**BEV**
2019	57.3%	3.2%	3.0%	31.1%	2.3%	1.5%	1.6%
2020	53.2%	4.1%	3.9%	31.0%	3.2%	2.3%	2.3%
2021	50.3%	4.9%	4.8%	29.8%	4.0%	3.0%	3.2%
2022	47.6%	5.5%	5.6%	28.6%	4.7%	3.6%	4.3%
2023	45.0%	6.0%	6.4%	27.4%	5.3%	4.3%	5.6%

2024	42.5%	6.4%	7.1%	26.2%	5.8%	4.9%	7.0%
2025	40.1%	6.8%	7.8%	25.1%	6.2%	5.4%	8.6%
2026	37.9%	7.1%	8.4%	24.0%	6.6%	5.9%	10.2%
2027	35.8%	7.3%	8.9%	22.9%	6.9%	6.3%	11.9%
2028	33.8%	7.5%	9.4%	21.9%	7.2%	6.7%	13.5%
2029	32.0%	7.7%	9.8%	20.9%	7.4%	7.1%	15.1%
2030	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2031	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2032	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2033	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2034	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2035	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2036	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2037	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2038	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2039	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2040	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2041	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2042	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2043	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2044	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2045	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%

2046	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2047	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2048	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2049	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%
2050	30.2%	7.8%	10.2%	20.0%	7.6%	7.4%	16.7%

Emission factor by Vehicle Type per Scenario

S1a - BAU

	ICE_gasoline	HEV_gasoline	PHEV_gasoline	ICE_diesel	HEV_diesel	PHEV_diesel	BEV
2019	209.3	121	58.7	201.9	109.9	53.4	0
2020	208.5	121.3	58.9	198.2	110	53.4	0
2021	207.8	121.5	59	195	110.1	53.5	0
2022	207.1	121.7	59.1	192.2	110.1	53.5	0
2023	206.5	121.8	59.2	189.7	110.2	53.5	0
2024	205.9	121.9	59.2	187.4	110.2	53.6	0
2025	205.3	122	59.3	185.4	110.2	53.6	0
2026	204.8	122.1	59.3	183.5	110.3	53.6	0
2027	204.3	122.2	59.4	181.7	110.3	53.6	0
2028	203.7	122.2	59.4	180	110.3	53.6	0
2029	203.2	122.3	59.4	178.4	110.4	53.6	0
2030	202.8	122.3	59.4	176.9	110.4	53.7	0
2031	202.3	122.4	59.5	175.4	110.4	53.7	0
2032	201.8	122.4	59.5	174	110.4	53.7	0
2033	201.4	122.4	59.5	172.6	110.4	53.7	0
2034	200.9	122.5	59.5	171.3	110.5	53.7	0
2035	200.5	122.5	59.5	170.1	110.5	53.7	0
2036	200.1	122.5	59.5	168.9	110.5	53.7	0
2037	199.7	122.5	59.5	167.7	110.5	53.7	0
2038	199.3	122.5	59.5	166.6	110.5	53.7	0
2039	198.9	122.5	59.5	165.6	110.5	53.7	0
2040	198.6	122.6	59.5	164.6	110.5	53.7	0
2041	198.2	122.6	59.5	163.6	110.5	53.7	0
2042	197.8	122.6	59.5	162.7	110.5	53.7	0
2043	197.5	122.6	59.6	161.8	110.5	53.7	0
2044	197.2	122.6	59.6	161	110.5	53.7	0
2045	196.8	122.6	59.6	160.2	110.5	53.7	0

2046	196.5	122.6	59.6	159.4	110.5	53.7	0
2047	196.2	122.6	59.6	158.7	110.5	53.7	0
2048	195.9	122.6	59.6	158	110.5	53.7	0
2049	195.6	122.6	59.6	157.3	110.5	53.7	0
2050	195.3	122.6	59.6	156.7	110.5	53.7	0

S1b - BAU + behaviour

	ICE_gasoline	**HEV_gasoline**	**PHEV_gasoline**	**ICE_diesel**	**HEV_diesel**	**PHEV_diesel**	**BEV**
2019	209.3	121	58.7	201.9	109.9	53.4	0
2020	208.5	121.3	58.9	198.2	110	53.4	0
2021	207.8	121.5	59	195	110.1	53.5	0
2022	207.1	121.7	59.1	192.2	110.1	53.5	0
2023	206.5	121.8	59.2	189.7	110.2	53.5	0
2024	205.9	121.9	59.2	187.4	110.2	53.6	0
2025	205.3	122	59.3	185.4	110.2	53.6	0
2026	204.8	122.1	59.3	183.5	110.3	53.6	0
2027	204.3	122.2	59.4	181.7	110.3	53.6	0
2028	203.7	122.2	59.4	180	110.3	53.6	0
2029	203.2	122.3	59.4	178.4	110.4	53.6	0
2030	202.8	122.3	59.4	176.9	110.4	53.7	0
2031	202.3	122.4	59.5	175.4	110.4	53.7	0
2032	201.8	122.4	59.5	174	110.4	53.7	0
2033	201.4	122.4	59.5	172.6	110.4	53.7	0
2034	200.9	122.5	59.5	171.3	110.5	53.7	0
2035	200.5	122.5	59.5	170.1	110.5	53.7	0
2036	200.1	122.5	59.5	168.9	110.5	53.7	0
2037	199.7	122.5	59.5	167.7	110.5	53.7	0
2038	199.3	122.5	59.5	166.6	110.5	53.7	0
2039	198.9	122.5	59.5	165.6	110.5	53.7	0
2040	198.6	122.6	59.5	164.6	110.5	53.7	0
2041	198.2	122.6	59.5	163.6	110.5	53.7	0
2042	197.8	122.6	59.5	162.7	110.5	53.7	0

2043	197.5	122.6	59.6	161.8	110.5	53.7	0
2044	197.2	122.6	59.6	161	110.5	53.7	0
2045	196.8	122.6	59.6	160.2	110.5	53.7	0
2046	196.5	122.6	59.6	159.4	110.5	53.7	0
2047	196.2	122.6	59.6	158.7	110.5	53.7	0
2048	195.9	122.6	59.6	158	110.5	53.7	0
2049	195.6	122.6	59.6	157.3	110.5	53.7	0
2050	195.3	122.6	59.6	156.7	110.5	53.7	0

S2-USC

	ICE_gasoline	**HEV_gasoline**	**PHEV_gasoline**	**ICE_diesel**	**HEV_diesel**	**PHEV_diesel**	**BEV**
2019	209.3	121	58.7	201.9	109.9	53.4	0
2020	208.5	121.3	58.9	198.2	110	53.4	0
2021	207.8	121.5	59	195	110.1	53.5	0
2022	207.1	121.7	59.1	192.2	110.1	53.5	0
2023	206.5	121.8	59.2	189.7	110.2	53.5	0
2024	205.9	121.9	59.2	187.4	110.2	53.6	0
2025	205.3	122	59.3	185.4	110.2	53.6	0
2026	204.8	122.1	59.3	183.5	110.3	53.6	0
2027	204.3	122.2	59.4	181.7	110.3	53.6	0
2028	203.7	122.2	59.4	180	110.3	53.6	0
2029	203.2	122.3	59.4	178.4	110.4	53.6	0
2030	202.8	122.3	59.4	176.9	110.4	53.7	0
2031	202.3	122.4	59.5	175.4	110.4	53.7	0
2032	201.8	122.4	59.5	174	110.4	53.7	0
2033	201.4	122.4	59.5	172.6	110.4	53.7	0
2034	200.9	122.5	59.5	171.3	110.5	53.7	0
2035	200.5	122.5	59.5	170.1	110.5	53.7	0
2036	200.1	122.5	59.5	168.9	110.5	53.7	0

2037	199.7	122.5	59.5	167.7	110.5	53.7	0
2038	199.3	122.5	59.5	166.6	110.5	53.7	0
2039	198.9	122.5	59.5	165.6	110.5	53.7	0
2040	198.6	122.6	59.5	164.6	110.5	53.7	0
2041	198.2	122.6	59.5	163.6	110.5	53.7	0
2042	197.8	122.6	59.5	162.7	110.5	53.7	0
2043	197.5	122.6	59.6	161.8	110.5	53.7	0
2044	197.2	122.6	59.6	161	110.5	53.7	0
2045	196.8	122.6	59.6	160.2	110.5	53.7	0
2046	196.5	122.6	59.6	159.4	110.5	53.7	0
2047	196.2	122.6	59.6	158.7	110.5	53.7	0
2048	195.9	122.6	59.6	158	110.5	53.7	0
2049	195.6	122.6	59.6	157.3	110.5	53.7	0
2050	195.3	122.6	59.6	156.7	110.5	53.7	0

S3-USC+LC

	ICE_gasoline	HEV_gasoline	PHEV_gasoline	ICE_diesel	HEV_diesel	PHEV_diesel	BEV
2019	209.3	121	58.7	201.9	109.9	53.4	0
2020	208.5	121.3	58.9	198.2	110	53.4	0
2021	207.8	121.5	59	195	110.1	53.5	0
2022	207.1	121.7	59.1	192.2	110.1	53.5	0
2023	206.5	121.8	59.2	189.7	110.2	53.5	0
2024	205.9	121.9	59.2	187.4	110.2	53.6	0
2025	205.3	122	59.3	185.4	110.2	53.6	0
2026	204.8	122.1	59.3	183.5	110.3	53.6	0
2027	204.3	122.2	59.4	181.7	110.3	53.6	0
2028	203.7	122.2	59.4	180	110.3	53.6	0
2029	203.2	122.3	59.4	178.4	110.4	53.6	0
2030	202.8	122.3	59.4	176.9	110.4	53.7	0
2031	202.3	122.4	59.5	175.4	110.4	53.7	0
2032	201.8	122.4	59.5	174	110.4	53.7	0
2033	201.4	122.4	59.5	172.6	110.4	53.7	0
2034	200.9	122.5	59.5	171.3	110.5	53.7	0
2035	200.5	122.5	59.5	170.1	110.5	53.7	0
2036	200.1	122.5	59.5	168.9	110.5	53.7	0
2037	199.7	122.5	59.5	167.7	110.5	53.7	0
2038	199.3	122.5	59.5	166.6	110.5	53.7	0
2039	198.9	122.5	59.5	165.6	110.5	53.7	0
2040	198.6	122.6	59.5	164.6	110.5	53.7	0
2041	198.2	122.6	59.5	163.6	110.5	53.7	0
2042	197.8	122.6	59.5	162.7	110.5	53.7	0
2043	197.5	122.6	59.6	161.8	110.5	53.7	0
2044	197.2	122.6	59.6	161	110.5	53.7	0
2045	196.8	122.6	59.6	160.2	110.5	53.7	0
2046	196.5	122.6	59.6	159.4	110.5	53.7	0
2047	196.2	122.6	59.6	158.7	110.5	53.7	0
2048	195.9	122.6	59.6	158	110.5	53.7	0

2049	195.6	122.6	59.6	157.3	110.5	53.7	0
2050	195.3	122.6	59.6	156.7	110.5	53.7	0

S4-Tech

	ICE_gasoline	**HEV_gasoline**	**PHEV_gasoline**	**ICE_diesel**	**HEV_diesel**	**PHEV_diesel**	**BEV**
2019	209.3	121	58.7	201.9	109.9	53.4	0
2020	208.5	121.3	58.9	198.2	110	53.4	0
2021	207.8	121.5	59	195	110.1	53.5	0
2022	207.1	121.7	59.1	192.2	110.1	53.5	0
2023	206.5	121.8	59.2	189.7	110.2	53.5	0
2024	205.9	121.9	59.2	187.4	110.2	53.6	0
2025	205.3	122	59.3	185.4	110.2	53.6	0
2026	204.8	122.1	59.3	183.5	110.3	53.6	0
2027	204.3	122.2	59.4	181.7	110.3	53.6	0
2028	203.7	122.2	59.4	180	110.3	53.6	0
2029	203.2	122.3	59.4	178.4	110.4	53.6	0
2030	202.8	122.3	59.4	176.9	110.4	53.7	0
2031	202.3	122.4	59.5	175.4	110.4	53.7	0
2032	201.8	122.4	59.5	174	110.4	53.7	0
2033	201.4	122.4	59.5	172.6	110.4	53.7	0
2034	200.9	122.5	59.5	171.3	110.5	53.7	0
2035	200.5	122.5	59.5	170.1	110.5	53.7	0
2036	200.1	122.5	59.5	168.9	110.5	53.7	0
2037	199.7	122.5	59.5	167.7	110.5	53.7	0
2038	199.3	122.5	59.5	166.6	110.5	53.7	0
2039	198.9	122.5	59.5	165.6	110.5	53.7	0
2040	198.6	122.6	59.5	164.6	110.5	53.7	0
2041	198.2	122.6	59.5	163.6	110.5	53.7	0
2042	197.8	122.6	59.5	162.7	110.5	53.7	0

2043	197.5	122.6	59.6	161.8	110.5	53.7	0
2044	197.2	122.6	59.6	161	110.5	53.7	0
2045	196.8	122.6	59.6	160.2	110.5	53.7	0
2046	196.5	122.6	59.6	159.4	110.5	53.7	0
2047	196.2	122.6	59.6	158.7	110.5	53.7	0
2048	195.9	122.6	59.6	158	110.5	53.7	0
2049	195.6	122.6	59.6	157.3	110.5	53.7	0
2050	195.3	122.6	59.6	156.7	110.5	53.7	0

S5-IA

	ICE_gasoline	**HEV_gasoline**	**PHEV_gasoline**	**ICE_diesel**	**HEV_diesel**	**PHEV_diesel**	**BEV**
2019	209.3	121	58.7	201.9	109.9	53.4	0
2020	208.3	120.6	58.6	198	109.1	53.1	0
2021	207.4	120.5	58.6	194.8	108.9	53	0
2022	206.6	120.4	58.6	191.8	108.7	52.9	0
2023	205.9	120.2	58.5	189.2	108.5	52.8	0
2024	205.1	120	58.4	186.7	108.3	52.7	0
2025	204.3	119.8	58.3	184.4	108	52.6	0
2026	204.3	119.8	58.2	184.4	108	52.5	0
2027	204.3	119.8	58	184.4	108	52.3	0
2028	204.3	119.8	57.8	184.4	108	52.1	0
2029	204.3	119.8	57.7	184.4	108	52	0
2030	204.3	119.8	57.5	184.4	108	51.8	0
2031	204.3	119.8	57.3	184.4	108	51.7	0
2032	204.3	119.8	57.2	184.4	108	51.5	0
2033	204.3	119.8	57	184.4	108	51.4	0
2034	204.3	119.8	56.8	184.4	108	51.2	0
2035	204.3	119.8	56.7	184.4	108	51	0
2036	204.3	119.8	56.5	184.4	108	50.9	0
2037	204.3	119.8	56.3	184.4	108	50.7	0
2038	204.3	119.8	56.1	184.4	108	50.5	0
2039	204.3	119.8	55.9	184.4	108	50.4	0
2040	204.3	119.8	55.7	184.4	108	50.2	0

2041	204.3	119.8	55.5	184.4	108	50	0
2042	204.3	119.8	55.3	184.4	108	49.9	0
2043	204.3	119.8	55.2	184.4	108	49.7	0
2044	204.3	119.8	55	184.4	108	49.5	0
2045	204.3	119.8	54.8	184.4	108	49.3	0
2046	204.3	119.8	54.6	184.4	108	49.1	0
2047	204.3	119.8	54.4	184.4	108	49	0
2048	204.3	119.8	54.2	184.4	108	48.8	0
2049	204.3	119.8	54	184.4	108	48.6	0
2050	204.3	119.8	53.8	184.4	108	48.4	0

S6-WC

	ICE_gasoline	**HEV_gasoline**	**PHEV_gasoline**	**ICE_diesel**	**HEV_diesel**	**PHEV_diesel**	**BEV**
2019	209.3	121	58.7	201.9	109.9	53.4	0
2020	208.5	121.3	58.9	198.2	110	53.4	0
2021	207.8	121.5	59	195	110.1	53.5	0
2022	207.1	121.7	59.1	192.2	110.1	53.5	0
2023	206.5	121.8	59.2	189.7	110.2	53.5	0
2024	205.9	121.9	59.2	187.4	110.2	53.6	0
2025	205.3	122	59.3	185.4	110.2	53.6	0
2026	204.8	122.1	59.3	183.5	110.3	53.6	0
2027	204.3	122.2	59.4	181.7	110.3	53.6	0
2028	203.7	122.2	59.4	180	110.3	53.6	0
2029	203.2	122.3	59.4	178.4	110.4	53.6	0
2030	202.8	122.3	59.4	176.9	110.4	53.7	0
2031	202.3	122.4	59.5	175.4	110.4	53.7	0
2032	201.8	122.4	59.5	174	110.4	53.7	0
2033	201.4	122.4	59.5	172.6	110.4	53.7	0
2034	200.9	122.5	59.5	171.3	110.5	53.7	0
2035	200.5	122.5	59.5	170.1	110.5	53.7	0

2036	200.1	122.5	59.5	168.9	110.5	53.7	0
2037	199.7	122.5	59.5	167.7	110.5	53.7	0
2038	199.3	122.5	59.5	166.6	110.5	53.7	0
2039	198.9	122.5	59.5	165.6	110.5	53.7	0
2040	198.6	122.6	59.5	164.6	110.5	53.7	0
2041	198.2	122.6	59.5	163.6	110.5	53.7	0
2042	197.8	122.6	59.5	162.7	110.5	53.7	0
2043	197.5	122.6	59.6	161.8	110.5	53.7	0
2044	197.2	122.6	59.6	161	110.5	53.7	0
2045	196.8	122.6	59.6	160.2	110.5	53.7	0
2046	196.5	122.6	59.6	159.4	110.5	53.7	0
2047	196.2	122.6	59.6	158.7	110.5	53.7	0
2048	195.9	122.6	59.6	158	110.5	53.7	0
2049	195.6	122.6	59.6	157.3	110.5	53.7	0
2050	195.3	122.6	59.6	156.7	110.5	53.7	0