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Citation for the original published paper (version of record):
de Oliveira Laurin, M., Selvakkumaran, S., Ahlgren, E. et al (2024). Are decarbonization strategies municipality-dependent? Generating rural road transport pathways
through an iterative process in the Swedish landscape. Energy Research and Social Science, 114.
http://dx.doi.org/10.1016/j.erss.2024.103570

Energy Research & Social Science 114 (2024) 103570

Contents lists available at ScienceDirect

Energy Research & Social Science

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

Review

Are decarbonization strategies municipality-dependent? Generating rural road transport pathways through an iterative process in the Swedish landscape

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ARTICLE INFO

Keywords:
Literature review
Local energy system
Non-urban road transport decarbonization
Pathways
Participatory approach
Semi-structured interviews

ABSTRACT

Energy transition studies, focusing on electricity and heating sectors, often consider a local energy system perspective. According to current state-of-the-art, a local energy systems perspective is yet and typically dismissed in the existing road transport decarbonization studies. Such studies tend to be limited to a national or global perspective, ignoring the challenges that rural areas may face. This study aims to develop a context-specific method that considers a local energy perspective when generating rural road transport decarbonization pathways. Literature review findings were iterated through participatory interactions with municipal officials from three Swedish municipalities, representing different-sized rural areas. Based on the municipalities' climate actions (fossil-free municipality targets) and the availability of local resources, five pathways were identified in an iterative and co-development manner. These pathways differed with respect to: (i) local electricity production; (ii) use of bio-sources; (iii) flexibility of public transport services; and (iv) tourism-related road traffic demands. The identified pathways were subjected to a qualitative performance assessment, which revealed that the local feasibility of each identified pathway depends on economic, environmental, and logistical factors. Although all identified pathways have the potential to contribute to the decarbonization of the municipalities' road transport systems, the municipalities preferred different pathways depending on their socio-economic, technical, and regulatory priorities.

1. Introduction

In line with the Paris Agreement, the European domestic transport sector is required to reduce its domestic greenhouse gas (GHG) emissions by up to 95 % by Year 2050, as compared to Year 1990 [1]. Yet, the decarbonization of the transport sector faces challenges that are related to two main transport-specific particularities. First, the transport sector is characterized by a heavy dependency on fossil fuels [2]. Second, the transport energy demand has historically followed the same increasing trend as economic growth [3,4]. In addition, road transport represents 69 % of the total European transport-related emissions [5]. Accordingly, meeting the European transport sector's emissions reduction targets, urges a rapid decarbonization of road transport, which in the past few years has resulted in different studies investigating how to solve the hurdles linked to this energy transition (see e.g., [6,7]). Studies assessing such an energy transition have often focused on the national level, ignoring the challenges that this decarbonization might pose at the local level. In this study, "local" is used to refer to a socio-geographic cluster that comprises different nodes in close proximity to each other, whereas "rural" describes a non-urban area, a "city" is part of a "municipality", and a "county" is part of a "region" that has multiple municipalities.

Addressing any energy transition at the local level requires an understanding of the local energy systems. As suggested by Groves et al. [8], local energy systems should be understood as a self-explanatory and dynamic concept that facilitates the incorporation of a diverse array of socio-technical contexts. Accordingly, local energy systems can be understood as networks established between the associated local energy supply-demand profiles and local end-users within a well-defined, self-contained area. Thus, local energy systems, in contrast to national and regional systems, facilitate an understanding of the implications that demand-side behaviors have on the local energy balance [9–12]. Some authors have highlighted the importance of adding a local energy system

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https://doi.org/10.1016/j.erss.2024.103570
Received 7 December 2023; Received in revised form 12 April 2024; Accepted 25 April 2024
Available online 22 May 2024

perspective when assessing energy transitions [13,14]. These studies have discussed how the decarbonization of any energy sector can benefit from local energy and climate awareness, which can be achieved by involving municipalities and encouraging them to decide on ambitious contributions towards meeting climate targets. Similarly, some reports have underlined the importance of assuming a local perspective when assessing the energy transitions of the electricity generation and heating sectors [15–18]. These studies have investigated energy transitions as a context-specific process and, thus, dependent upon the local conditions of the system under study. Such conditions can be energy sources that are locally available, energy demand patterns, technology readiness, and policy frameworks [19–26].

To achieve decarbonization of road transport, in terms of the local level, important conditions to consider include: travel patterns (such as car ownership and driving distances); vehicle specifications; fuel consumption profiles; and traffic regulations [27–32]. Such conditions, as highlighted by Cheyne et al. [33], Silvestri et al. [34], and Corradi et al. [35], are socio-economic and socio-demographic variables that are specific to a socio-geographic context. As these conditions are specific for a socio-geographic context, they influence the decarbonization potentials of fuel and mobility technologies. Rural areas, as compared to urban areas, are characterized by higher levels of car dependency, longer travel distances, and both inadequate and insufficient public mobility infrastructure and connectivity (e.g., scarcity of public charging stations, lack of and inefficient public transport services, non-existent bicycle lanes), conditions that can further hinder the decarbonization of their transport systems.

Road transport decarbonization in rural areas is still under-investigated, with only a few studies having been published, in which fleet electrification [36–40] and public transport services [41–43] are often presented as the low-carbon solutions that have the strongest potential to be implemented in rural areas. Xu et al. [36] have optimized the electrification of the car fleet, by minimizing the electricity grid impact and constraining the charging to a local level. Suttakul et al. [37], by assessing traffic and congestion profiles (i.e., driving patterns in rural areas), have found that electrifying the car fleet is the most energy-efficient powertrain solution, both in terms of energy consumption as well as carbon dioxide (CO_2) emissions reduction. Nilsson et al. [38] have pointed out that electrifying the car fleet in rural areas can be regarded as feasible only if it satisfies the specific mobility needs of rural areas. In a policy-oriented study, the authors have highlighted the roles that government actions (e.g., subsidization of battery-electric vehicles [BEVs] and economic support for investments in charging infrastructure, such as fast, super-fast, and home chargers) can play in accelerating the electrification of car fleets [38]. Köhler et al. [39] have performed a simulation study that analyzes the interactions and dynamics of the rural area-specific technological, institutional, and socio-cultural factors that shape the decarbonization pathway for road transport systems. According to the authors, electrifying the car fleet, despite the challenges associated with its implementation in rural areas, is revealed to be a good decarbonization strategy [39]. Walters et al. [40] believe that electrification of the car fleet, when combined with connected (i.e., a car that is equipped with advanced communication technologies that enable it to connect to its surroundings, the internet, other vehicles, infrastructure, and external systems [44]) and autonomous (i.e., a self-driving car, capable of navigating and operating without human intervention [45]) transport technologies, can not only reduce emissions but can also lead to safer, more-efficient, and more-accessible rural road transport systems. Bell et al. [41] have proposed that a modal shift from private cars to public and electrified transport services could support road transport decarbonization in rural areas. However, rural areas are still lacking fair access to these services. The main reasons for the lack of access to public transport in rural areas are the poor infrastructure and the unbalanced operational management of these services, which are typically regulated at a regional level and tend to ignore local travel patterns [41]. Furthermore, Li et al. [42] and Enoch et al. [43] agree that public transport services require a comprehensive analysis of travel behaviors. Both authors, by modeling different travel patterns scenarios, have identified the impacts that different public transport accessibility levels have on CO_2 emissions reductions [42,43].

Two knowledge gaps were identified in the above-described state-of-the-art. First, there are very few reported studies on rural road transport and the existing ones assess transport as an isolated system. As with any other energy transition, rural road transport decarbonization should not be restricted to a conceptual perspective but be complemented by and adjusted to the local conditions [46]. This limitation can be overcome by using an integrated energy system perspective that will capture cross-sectoral dynamics [47,48]. Capturing cross-sectoral linkages enables the identification of system integrators, which are local resources, technologies, and processes that find applications in different parts of a local energy system, and their identification provides an understanding of both potential synergies and conflicts that occur between different local sub-energy systems [49–52]. Therefore, the decarbonization of rural road transport systems benefits from having a comprehensive picture of the local context and its socio-technical conditions, which can be achieved by developing decarbonization pathways for road transport [53].

Second, no study was found that addresses the decarbonization of road transport through generation pathways based on a participatory approach. Generating decarbonization pathways is a commonly used method to cope with system complexity and challenges associated with the decarbonization of Society [54–57]. Such pathways can depict multiple potential futures and the balance between different technical and socio-economic transition aspects in a given context [58]. Thus, the pathways may delineate the key strategies for an energy transition and efficient ways of allocating resources within a system under transition [53,59–64]. Hence generating pathways, when used as an understanding tool of energy system transitions, calls for a comprehensive and integrated perspective of energy systems, thus benefiting from the adoption of a collaborative and interdisciplinary dimension [65–67]. Such a dimension can, for example, result from combining a literature review of energy system analyses with local policymakers' and actors' stated preferences (social science), while adopting a so-called "participatory approach". This approach involves local stakeholders, who provide specific local knowledge regarding socio-geographic specifications, as well as information on how local communities function and how local utilities operate [58,68,69]. As stressed by Sarrica et al. [70], assuming a participatory approach within the energy field enriches the understanding that energy transitions are not prescriptive, but rather a result of local interactions and thus, should be tailored to a specific socio-geographical context. Thus, assuming a participatory approach can, as explained by Späth et al. [71], further support energy planning and decision-making. Accordingly, bridging the gap between generating pathways and a participatory approach facilitates a system perspective, which strengthens the feasibility of the energy transition.

Overall, existing research on road transport decarbonization often takes a narrow national perspective. This approach links road transport understanding to national-level data, often using weighted average values. However, relying solely on these averages tends to prioritize urban travel patterns, obscuring the unique challenges faced in rural areas. Neglecting the local context of road transport decarbonization can lead to a misalignment between municipality climate commitments and broader regional and national climate goals. This misalignment not only burdens municipalities with responsibility but also imposes economic constraints on their ability to invest in necessary changes. Consequently, the cost of potential delays in meeting climate goals is borne not only by municipalities but also by regional and national entities.

The overarching aim of this study is, thus, to elucidate the decarbonization of rural road transport by adopting a local energy systems perspective. Specifically, the study aims to: (i) explain how different road transport pathways can be generated and tailored to a specific socio-geographical context by iterating different phases of literature review and participatory approach; and (ii) clarify how these pathways, as a result of a developed context-specific and iterative method, can contribute with knowledge to the decarbonization of rural road transport systems. Within the context of the local energy systems under study, this study aims to emphasize the importance of customizing road transport decarbonization efforts to the unique socio-geographic context undergoing transition. In doing so, it offers a practical contribution to national and regional stakeholders by introducing a new top-down dimension to not only road transport decarbonization but also the broader energy transition. Stakeholders can benefit from this research by comparing it with existing actions outlined in national and regional roadmaps while recognizing the complexity of adopting a "one-size-fits-all" strategy. Accordingly, the main questions addressed here are: RQ.1. How can pathways be generated that better support the road transport sector decarbonization in local and rural contexts?; and RQ.2. Which road transport pathways are feasible for supporting rural transport sector decarbonization based on applying the method developed in RQ.1 to the cases of three Swedish municipalities?

This study is structured as follows: the development of a context-specific method is described in Section 2. In Section 3, the local energy system contexts of three rural Skaraborg municipalities in region Västra Götaland, Sweden are described. In Section 4, the developed method is further applied and implemented in the three Swedish municipalities. The end-users considered are road transport (focusing on private cars and public transport), heating, and electricity distribution systems. Each of the three end-use sectors is introduced as a sub-local energy system. A discussion and concluding remarks of the method and its application to a real case is presented in Section 5.

2. Method

In this study, the decarbonization of road transport systems was investigated using a context-specific iterative method that was developed for the specific purpose of generating pathways. The method was applied to the local context of rural areas. As a context-specific method, the pathways are generated by assuming a local energy system perspective, thereby capturing the conditions of the rural context being studied.

The method was developed in an iterative manner that combines different phases of both conceptual and mainly technological literature review findings with the qualitative storylines, resulting from a participatory approach. The iterative dimension of our method establishes a complementary loop between different phases of literature review and participatory engagement with municipal officials (i.e., participatory approach). This iterative process strengthens the credibility of both method development and the resulting identified pathways. It effectively addresses limitations in the literature review, particularly in recognizing that some non-carbon transport solutions may not align with the current social, political, and economic environment of different socio-geographical contexts. Additionally, such a loop facilitates the management of a participatory approach, while helping stakeholders to navigate challenges associated with long-term uncertainties.

The participatory approach adopted in this study followed the guidelines applied previously [68,72,73]. Using a participatory approach, Stalpers et al. [68] have highlighted the importance of stakeholder involvement when deciding on the GHG emissions reduction strategies to be applied on Dutch dairy farms. Karlsson et al. [72] have applied a participatory approach to assess the feasibility of achieving net-zero carbon emissions in the supply chain of the Swedish road construction sector. Yu et al. [73], by including Danish heating systems and urban planning stakeholders, have applied a participatory approach to identify which (and how) aspects of the urban planning process should be considered when designing an energy systems model.

The method developed, as outlined in Fig. 1, has three main stages: Data and Literature Review; Participatory Interaction; and Pathways Generation. These three stages will be presented in detail in the following sections.

2.1. Data and literature review

The aim of the first stage is to gain a local understanding of specific rural contexts, in order to clarify how decarbonization pathways for road transport can be generated. Thus, specific data on local energy systems, including demand profiles, structure and operation of local road transport, heating, electricity distribution, local infrastructure, technology readiness, and sector coupling, were taken into consideration.

2.1.1. Literature review – Phase 1: conceptual transport pathways

A literature review was conducted on the fuel and mobility options for road transport decarbonization. Reviewing published scientific literature is an important part of our iterative research approach, and the outcome is tied to the search process and search string used. The approach and guidelines used for this literature search are depicted in Fig. 2. The peer-reviewed scientific literature on road transport decarbonization was retrieved and compiled by searching for the same keywords in the SCOPUS and Web of Science online databases. Specifically, the literature was filtered and selected according to a search string in the

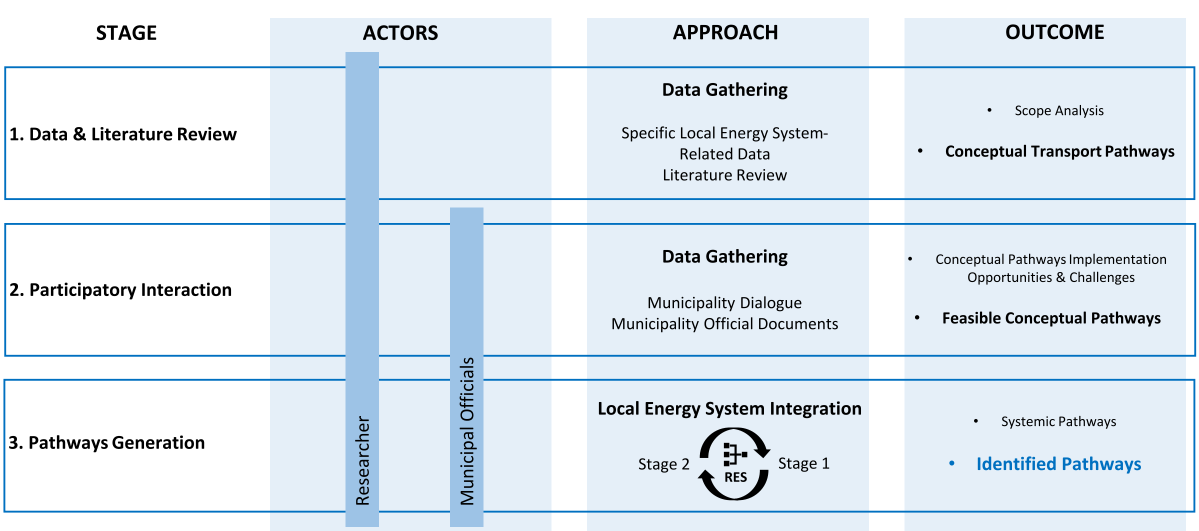

Fig. 1. Outline of the method developed and implemented in this study. RES, Reference Energy System.

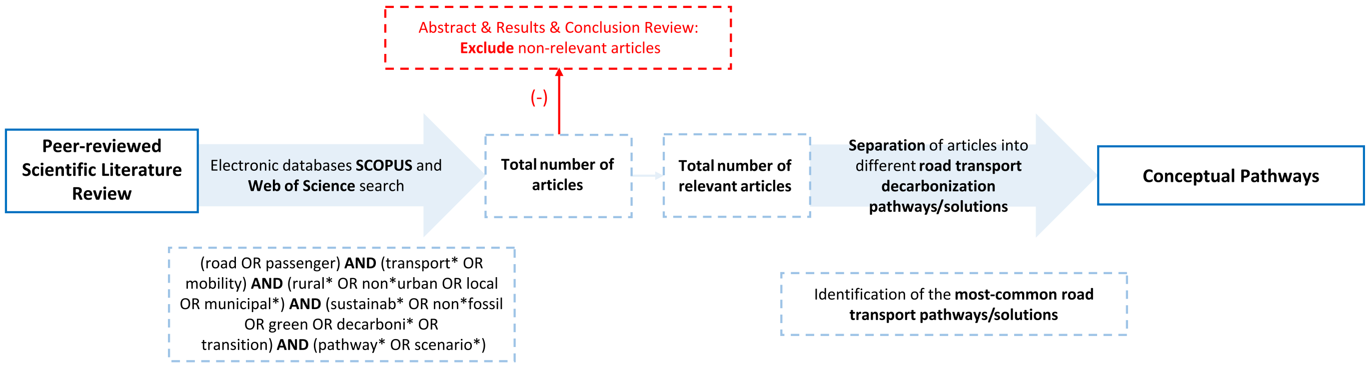

Fig. 2. Protocol for the literature review conducted in this study, adapted from [74,75].

Title, Abstract, and Keywords fields. The search string was (road OR passenger) AND (rural* OR non*urban OR local OR municipal*) AND (transport* OR mobility) AND (sustainab* OR non*fossil OR green OR decarboni* OR transition) AND (pathway* OR scenario*). The asterisks (*) in the search string allowed searches for words derived from the given term. The logic operator "AND" between the different commands excluded all literature that would fulfill each command individually. Moreover, the literature review was limited to English-language publications that appeared after the signing of the Paris Agreement in 2015. Other studies that previously have used the same guidelines and literature review protocol are e.g., Schulze et al. [74] and Selvakkumaran et al. [75].

The studies found in the two databases were filtered, initially using a manual process to go through all the abstracts. If the abstract was judged to be interesting but vague regarding the relevance, the results and conclusions sections were also read. The selected relevant articles were analyzed, and then categorized according to the particular road transport decarbonization pathways and solutions that were suggested. As an outcome, this stage identified the most-common road transport decarbonization pathways and solutions suggested in the literature, which, in this study, are defined as conceptual pathways.

2.2. Participatory interaction

As with any energy transition, road transport decarbonization is context-specific and, therefore, it is beneficial if complemented with a local energy system perspective. A local energy system perspective provides an overview of the system's composition, as well as an understanding of how the system operates. This overview clarifies how the different parts of the system are interlinked (e.g., the different energy end-use activities that share the same supply resource). Thus, it is possible to predict a system's response to the implementation of a specific action (e.g., decarbonization). Accordingly, for a given action to be implemented, it is possible to identify the system enablers (i.e., the parts of the system that support the implementation of a given action, as such an implementation does not affect the system's performance) and bottlenecks (i.e., parts of the system that might be sensitive to the implementation of a given action). In this study, the local energy system perspective was ensured by involving municipal officials, through a participatory approach.

2.2.1. Municipal officials' participation – Phase 1

Assuming a participatory approach has been described by Salter et al. [76] as an effective way to engage stakeholders, and any type of research can benefit from acquiring stakeholder experiences, knowledge, and perspectives. Moreover, a participatory approach, as discussed by Colenbrander et al. [77], allows for close collaboration between researchers and local authorities, resulting in a more-detailed understanding of local energy systems. In the context of the energy transition, as the authors explain, assuming a participatory approach manages the transition so as to avoid exacerbating the techno-economic, political, and social conflicts within the current system [77]. Stage 2, as depicted in Fig. 3, was developed in a participatory manner, meaning that the conceptual pathways identified in Stage 1 were filtered according to the judgments of municipal officials and analyses of official municipal documents. For this process, entities with which it was deemed desirable to establish contact were identified, based on the knowledge acquired during Stage 1, meaning that municipal officials were selected according to how suitable their roles were in relation to the scope of this study.

2.2.1.1. Preparation. The contacts with the identified municipal officials were initiated through e-mail communication. A first email describing the research scope and highlighting how municipalities could contribute to and gain from being involved in the present research was sent to the municipal officials. Accordingly, the municipal officials were invited to participate in the present research project using the format of semi-structured interviews. When municipal officials agreed to be interviewed, before the interview meeting between the researchers and municipal officials, a questionnaire was sent out to these officials.

The goal of the questionnaire was not only to present the conceptual pathways identified in Stage 1, but also to gauge the opinions of the officials regarding the potential implementation of these pathways in their municipalities. Thus, the questions were formulated to understand how well the conceptual pathways could fit into the local contexts of the participating municipalities. Accordingly, the questions concerned: (i) a local energy system description, with emphasis on road transport, electricity, and heating systems, including both the demands for and availability of local resources (e.g., variable renewable energy sources [VRES], biomass, and biogas) and infrastructure (e.g., public charging stations); (ii) clarification of the municipalities' environmental planning (e.g., goals and challenges) towards the decarbonization of local road transport; and (iii) an understanding of the decision-making process regarding road transport, at the local level, and how this process interacts with both regional and national decision-making planning. The interviewees were encouraged to reflect on the questionnaire and to evaluate and define the potentials and challenges linked to the conceptual pathways if integrated into their context. Subsequently, as part of the participatory approach process, the conceptual pathways were analyzed and discussed by the researchers and municipal officials in a semi-structured interview format.

2.2.1.2. Semi-structured interviews. As Hollway et al. [78] have explained, semi-structured interviews, as a common way of supporting the integration of a participatory approach, follow a set of predetermined questions, outlining the main topics to be asked. Yet, these questions are defined as being open-ended, meaning that they are flexible enough to allow follow-up questions, but also to explore topics of interest mentioned during the interview. Since they are participant-centered, semi-structured interviews focus on personal narratives and

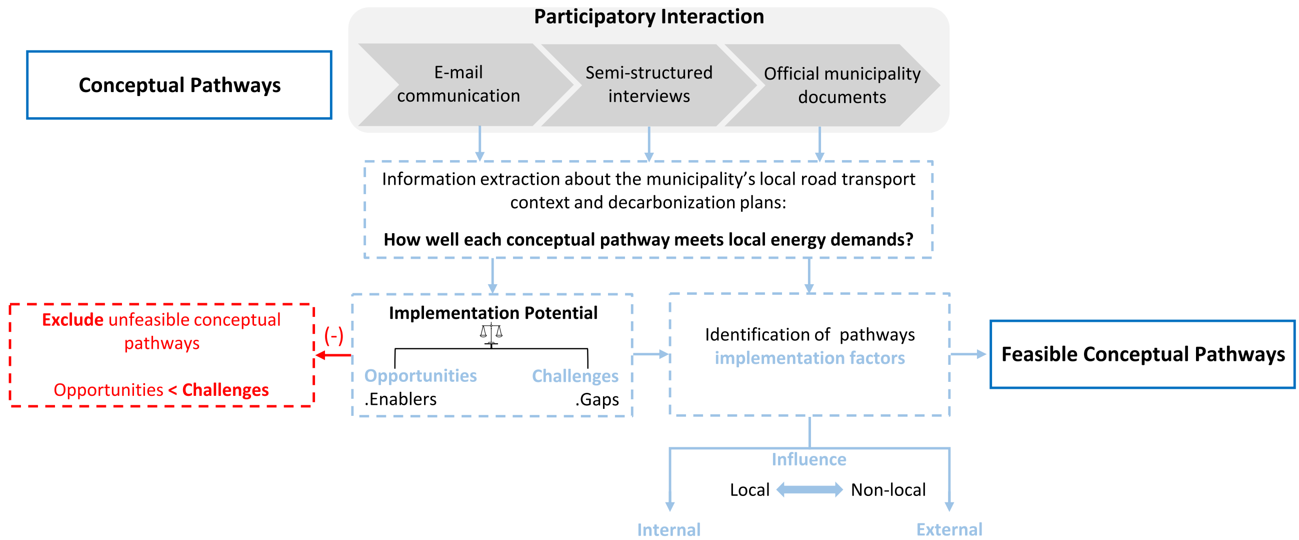

Fig. 3. Flowchart for the Participatory Interaction Stage. The gray arrows represent the sequential paths through which the contacts between the researchers and municipal officials were established. The dashed-line boxes represent intermediate approaches and outcomes that led to the identification of conceptual pathways that could be feasibly integrated into the municipal context under study. The solid-line boxes represent the inputs and the outputs of the Participatory Interaction.

insights. This allows for a detailed understanding of the participant's responses, providing the opportunity to delve into specific details [78]. Accordingly, semi-structured interviews were carried out in this study as one of the sequential paths through which the contacts between the researchers and municipal officials were established (see gray arrows in Fig. 3). The semi-structured interviews follow the set of predetermined questions previously shared with the participating municipal officials in a digital questionnaire format. Those questions are thoroughly presented in the appendix (see Questionnaire presented in A.1). During the semi-structured interviews carried out for this study, the conceptual pathways were reviewed (in cooperation with the targeted municipalities) regarding their abilities to cope with the conditions of a given local context. This assessment was based on weighing the implementation potential of each of the conceptual pathways in terms of how well each pathway could meet the local energy demands of the different municipalities. The implementation potential was a descriptive metric that was used in this study to compare the conceptual pathway enablers (i.e., opportunities) with the gaps (i.e., challenges). For each conceptual pathway, this metric could be either positive (i.e., the opportunities exceed the challenges) or negative (i.e., the opportunities exceed the challenges).

The positively evaluated conceptual pathways were discussed regarding which factors could influence their implementation potential. These implementation factors were perceived by the municipalities as socio-economic, technical, and regulatory factors. Such factors can act as either enablers or barriers to certain technologies, travel patterns, and local energy demands, when experienced in the local context of the municipality. These factors were considered by the municipal officials to vary according to what the municipality had in its power to decide and control. That is, for some of these factors, the decision-making is under the control of the municipality, whereas other factors, regardless of their impacts on issues of value for the municipality, are controlled by decisions made outside the municipality.

For clarification, this study refers to these factors as being either internal or external factors. Internal factors are aspects that can be controlled, established, and managed according to the municipality's vision. External factors incorporate actions that are happening at a non-local level and over which the municipality lacks significant influence, although it needs to readjust its local actions accordingly. In this study, external factors are considered to happen at the national, regional, and individual levels. The reason why individual factors are included in this study has to do with the roles that individuals play in road transport. Individuals are the primary users and stakeholders of road transport, and every day, according to their preferences and needs, they deliberate on their own vehicle choices, route selection, and travel patterns [79].

2.2.2. *Feasible conceptual pathways*

Stage 2 of the research, as depicted in Fig. 3, culminated with the review and analysis of official documents that municipal officials cited during the interviews and later shared with the research team. As a direct outcome of this process, only the conceptual pathways that were positively evaluated, and therefore regarded as feasible to be implemented in the interviewed municipalities, were considered in the subsequent steps of the project.

2.3. *Pathways generation*

Stage 3, the final stage of this method, was developed with the purpose of generating road transport decarbonization pathways. The pathways were iteratively generated based on the Data and Literature Review, as well as the Participatory Interaction Phases, as illustrated in Fig. 4. Moreover, the performance levels of the identified pathways were qualitatively evaluated according to different assessment criteria. Overall, Stage 3 added a layer to the feasible conceptual pathways that were identified in Stage 2, with a description of the implications that the implementation of these pathways could have on the local energy system. This additional layer was depicted in a qualitative Reference Energy System (RES), in which cross-sectoral linkages and system integrators were identified.

2.3.1. *Cross-sectoral understanding*

2.3.1.1. Literature review – Phase 2. Including only the pathways that were deemed to be locally feasible by municipal officials might lead to a biased and inadequate representation of the local energy system [80]. This risk was mitigated in Stage 3 through iterative feedback between Stage 1 – Data and Literature Review – and Stage 2 – Participatory Interaction. Thus, a second literature review (i.e., corresponding to Phase 2 in Fig. 4), specifically aimed at investigating the implications that each of the so-far positively evaluated feasible conceptual pathways might have for the whole local energy system, was conducted. Specifically, the studies reviewed in Stage 1 that addressed decarbonization of road transport systems according to a cross-sectoral perspective were re-analyzed. To ensure good coverage of the analyzed cross-sectoral

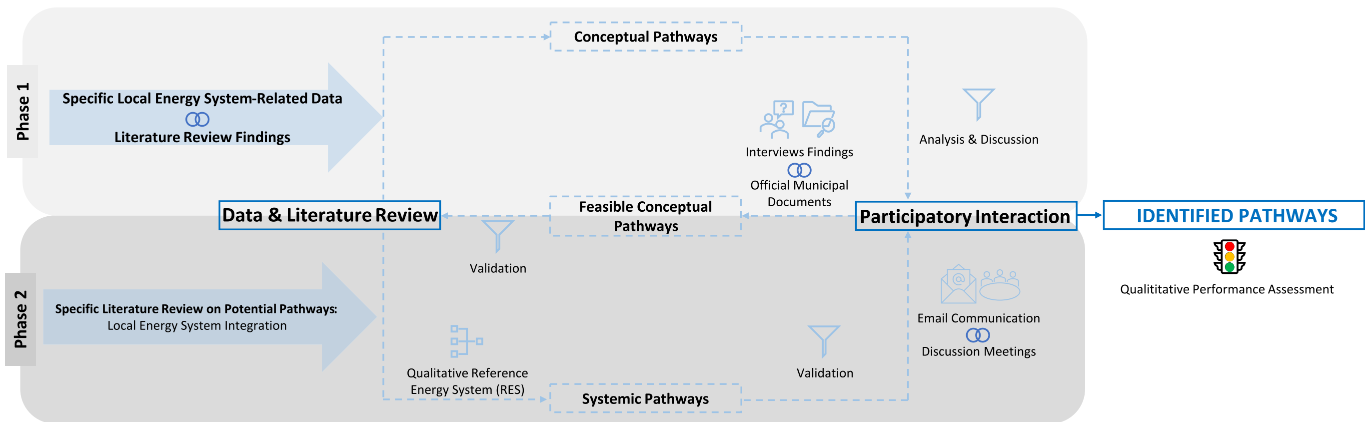

Fig. 4. Development framework based on an iterative approach with two phases – Phase 1 (light-gray-shaded rectangle) and Phase 2 (dark-gray-shaded rectangle) – of the Data and Literature Review and the Participatory Approach Stages, to generate several types of pathways that are subsequently used to identify the rural road transport decarbonization pathways ("Identified Pathways").

studies, the new literature review added the following search commands to the search string used in Stage 1: (cross*sector* OR sector*coupl* OR inter*sector* OR multi*sector) AND (electric* OR heat*). The protocol followed in this phase of the literature review is thoroughly presented in the Appendix (see Fig. A 1).

2.3.1.2. Qualitative reference energy system. Assuming a cross-sectoral perspective entailed a qualitative local RES, which is defined as a representative network of the energy flows between different end-use activities, with the network being supplied by diverse forms of energy [81]. The RES constructed in this study incorporated the local road transport (private cars and public transport – buses), heating, electricity distribution systems, and their interactions. Consequently, this study assessed the integrative roles that some local resources play across the local energy system (i.e., system integrators). Identifying system integrators increased awareness of possible cross-sectoral synergies and competition for both local development and financing.

2.3.1.3. Systemic pathways. Returning to a literature review, focusing on a cross-sectoral perspective, clarified the impacts that the feasible conceptual pathways could have on the local energy system (the pertinent question here is: In case one of the feasible conceptual pathways supports an increase in the utilization of a specific energy resource within the road transport system, what consequences would the surge for that resource's demand have on the effective operation of other energy systems that are also reliant on this resource?). Such a clarification leads to the identification of systemic pathways that, in this study, are the conceptual pathways selected in Stage 2 (Participatory Interaction), with an additional understanding of their local energy system-responsive impacts.

2.3.2. Municipal officials' participation – Phase 2

The systemic pathways were subsequently validated qualitatively by returning to the Participatory Interaction Stage (i.e., corresponding to Phase 2 in Fig. 4) for a second round of meetings with the municipal officials. The systemic pathways were presented and described to the municipal officials via e-mail and discussion meetings. The focus was on which type of fuel or mobility technology was suggested in each of the systemic pathways. In addition, the systematic pathways were presented in a cross-sectoral perspective, highlighting the consequences that their implementation could have on the overall local energy system. Accordingly, the municipal officials were asked to provide a final assessment of the local feasibility levels of the systemic pathways. The municipal officials were also encouraged to add details to the systemic pathways presented, to enhance cross-sectoral understanding.

2.3.3. Identified pathways

This final feasibility evaluation considered the targeted local energy system context, its mobility patterns, and other local energy demand profiles (e.g., the electricity and heating demands of the municipality), as well as national climate actions. This resulted in the generation of rural road transport decarbonization pathways ("Identified Pathways"). The performances of the identified pathways were qualitatively evaluated and discussed by the research team in line with various assessment criteria. This evaluation applied a "traffic light" color scheme, which is a visualization tool previously described by Gray et al. [82]. Those authors only used the tool as an efficient way to present in a comparative manner the performances of different road, marine, and aviation fuel pathways [82]. The present study further expands the use of this tool to a discussion-comparison method, which for each of the considered criteria, facilitates the ranking of the relative performances of the identified pathways. The criteria for this assessment were selected during the Participatory Interaction Stage, through collaborative discussions between the researchers and municipal officials. For each criterion evaluated, each pathway, based on its performance, was labeled with one of the three typical traffic light colors, with red, yellow, and green corresponding to poor, neutral, and good performances, respectively. This qualitative performance assessment made it possible to identify those identified pathways that had the best and the worst performances based on a given criterion.

3. Case overview

Skaraborg is a county located in the west of Sweden and belongs to the Västra Götaland region (see Fig. 5). Skaraborg is composed of diverse types of cities and rural municipalities that differ in relation to their local energy demand profiles, existing infrastructure, potential for implementing VRES, financial constraints, policy barriers, and social behaviors. As Skaraborg provided a strong local system perspective, it was selected as a case study.

Within Skaraborg county, six municipalities committed to participate in this study. In line with the classification presented by the Swedish Association of Local Authorities and Regions [83,84], these six municipalities are described as non-urban municipalities according to the following terminology: *mindre stad/tätort* (small cities); *pendlingskommun nära mindre stad/tätort* (commuting municipalities near a small city); and *pendlingskommun nära större stad* (commuting municipalities near a medium-sized city). For the interviews, a municipality representative of each of the above types was chosen. It is important to note that in this study any non-urban municipality was referred to as a "rural municipality".

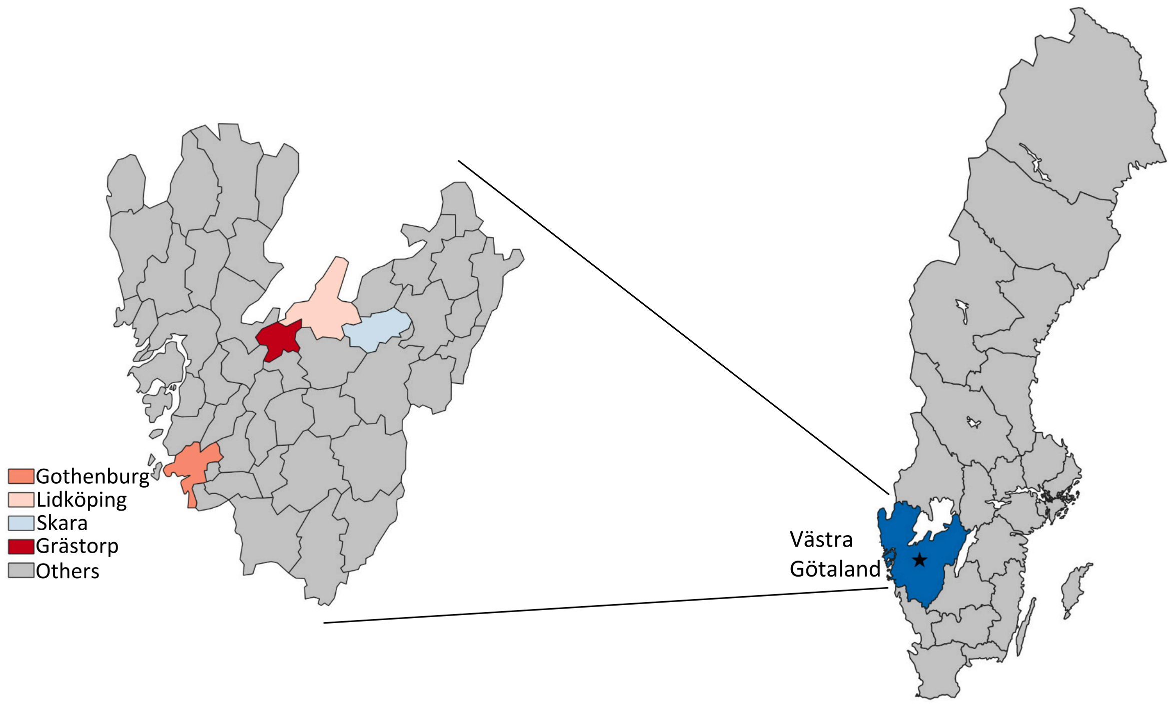

Fig. 5. Left map: The Västra Götaland region. Only the municipalities considered in this study are colored. Right map: Map of Sweden, indicating the Västra Götaland region in blue. Data retrieved from [85]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The rural municipalities that participated in this study were Lidköping, Skara, and Grästorp, which are defined, respectively, as: a small city (a municipality with a minimum population of 15,000 within the largest urban area); a commuting municipality near a small city (a municipality in which either >30 % of the working population commutes to work from a small city or >30 % of the employed during daytime population resides in a different municipality); and a commuting municipality near a medium-sized city (a municipality in which >40 % of the working population travels to a medium-sized city for work).

The choice of these municipalities is evident when considering their mobility trends and comparing them with typical trends experienced at a larger city level (in Swedish: *storstäder*, which are municipalities with at least 200,000 inhabitants in the largest urban area). In this study, Gothenburg was used to represent a larger city and, thus, exemplifies the urban context.

The annual distance traveled, per person, for a given transport mode was calculated for each of the assessed municipalities, according to Eq. (1). Thus, the annual distances traveled were calculated by multiplying

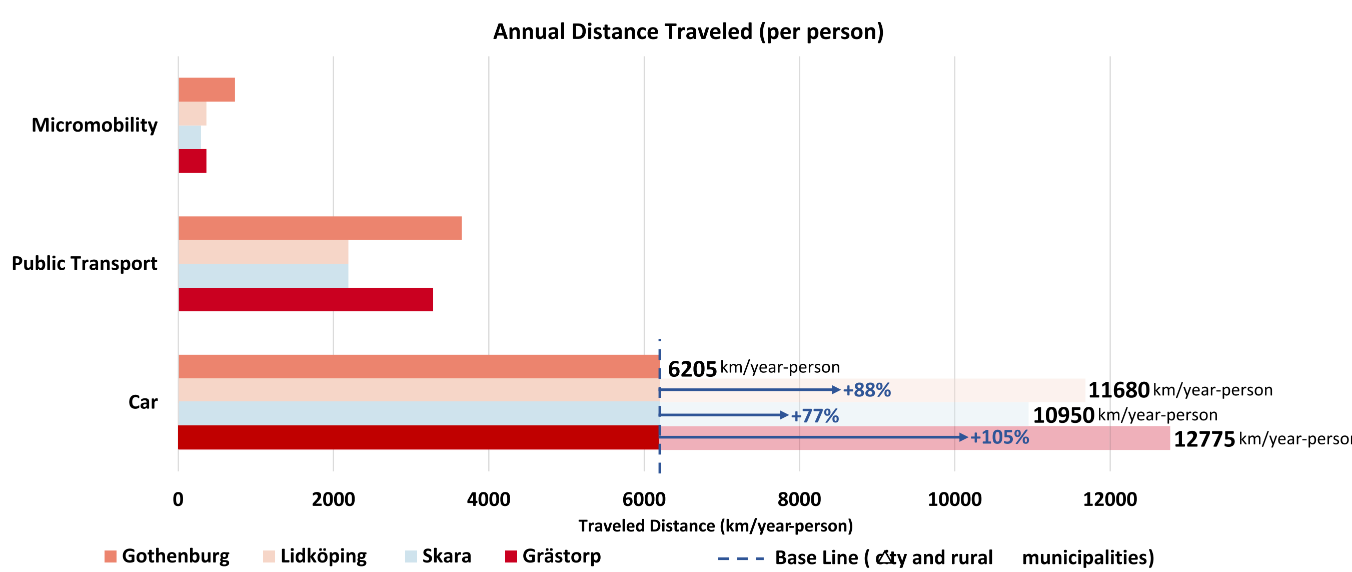

Fig. 6. Annual distance traveled per person for three modes (car, public transport-buses-, and micromobility) for each of the three participating municipalities and Gothenburg. Data retrieved from [86]. The data used in this study refer to Year 2019, the year before the COVID-19 pandemic, so the values are considered a more-accurate starting point for assessing pathways. The blue dashed-line indicates the difference between Gothenburg and the three rural municipalities (Lidköping, Skara, and Grästorp). The blue arrows and corresponding blue values illustrate the differences, in percentages, of the annual distances traveled per person, for each of the three considered transport modes, in each of the participating municipalities, as compared to the corresponding values for Gothenburg. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the daily distance traveled using a given mode, per person [86] (see Table B 1) by the year length of 365 days. This calculation was carried out for each of the three considered road passenger transport modes: cars, public transport, and micromobility (cycling and walking).

$$\text{Annual distance travelled by a transport mode per person}\left(\frac{\frac{km}{year}}{person}\right) = \text{Daily distance traveled}\left(\frac{\frac{km}{day}}{person}\right) * \text{Annual distribution (365 days)} \tag{1}$$

$$\text{Annual } CO_2eq \text{ Emission}\left(\frac{\frac{kgCO_2eq}{year}}{car}\right) = \text{Annual distance travelled by car per person}\left(\frac{\frac{km}{year}}{person}\right) * \text{Car occupancy}\left(\frac{person}{car}\right) * \sum_{\text{fuel type}}[\text{Share in the total car fleet (\%)}] * \sum_{\text{fuel type}}\left[\text{Carbon content}\left(\frac{gCO_2eq}{km}\right)\right] * \frac{1}{1000}\left(\frac{kg}{g}\right) \tag{2}$$

It is clear from Fig. 6 that both urban and rural municipalities are strongly car-dependent. It should, however, be noted that the annual distance traveled per car is, on average, 90 % higher in the considered rural municipalities, as compared to the corresponding values for Gothenburg. Public transport and micromobility are both shown to have a higher share in Gothenburg, as compared to the three municipalities under study.

The annual carbon dioxide equivalent (CO_2-eq) emissions level from car usage, per car, was also calculated according to Eq. (2). The annual CO_2-eq emission level (per fuel type) is obtained by multiplying the annual distance traveled by car per person [a direct outcome of Eq. (1)] by the average national car occupancy of 2.22 persons/car [87], by the share that a given fuel type represents in the total car fleet [88], as well as by the carbon content associated with the use of this fuel type [89] (see Tables B 2 and B 3). Thereafter, the total annual CO_2-eq emission level from car usage is derived by summing the annual CO_2-eq emissions of the different fuel types associated with car usage. The fuel types considered in this study are gasoline, diesel, electricity (both BEVs and plug-in electric vehicles), bioethanol, and gas (a mixture of 10 % natural gas and 90 % biogas). The results for the studied municipalities are presented in Fig. 7.

The high levels of car usage in Lidköping, Skara, and Grästorp generate high levels of emission; the three municipalities are, on average, responsible for 41 % higher CO_2-eq emissions from passenger cars, as compared to Gothenburg (Fig. 7).

Despite the high levels of car dependency in these municipalities, all the municipalities in the Västra Götaland region show a commitment to reducing their carbon footprints and meeting the national climate goal, whereby Sweden aims to have net-zero emissions of GHGs into the

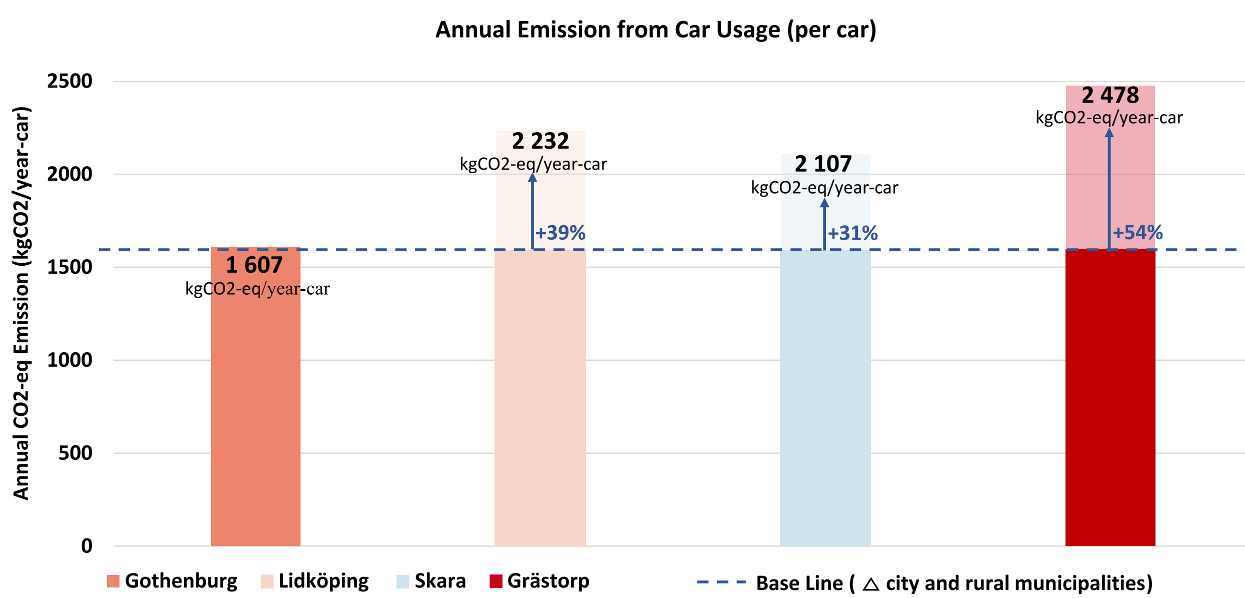

Fig. 7. Annual CO2-eq emissions resulting from car usage (kgCO2 per car) in the different municipalities under study. Data retrieved from [87–89]. The data used in this study refer to Year 2019, the year before the COVID-19 pandemic, so the values are considered a more-accurate starting point for assessing pathways. The blue dashed-line delineates the differences between the larger city (Gothenburg) and the rural municipalities (Lidköping, Skara, and Grästorp). The blue arrows and corresponding blue values illustrate the differences, in percentages, in the annual CO_2-eq emissions from car usage, per car, in each of the participating municipalities, as compared to the corresponding values for Gothenburg. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

atmosphere by Year 2045 [90]. All of the Swedish regions, including the municipalities in Västra Götaland, have a collective obligation to contribute towards meeting this goal.

In this context, these municipalities have signed the *Klimat30* agreement, which ambitiously sets municipal domestic independence from fossil fuels and climate neutrality to Year 2030 [91]. This will entail reducing the total GHG emissions by 80 % compared to the Year 1990 level. Following on this commitment, region Västra Götaland and its municipalities are identifying and tackling issues that fall under the concept of sustainable mobility from the environmental, social (accessibility and gender equality), and economic perspectives. Later, these municipalities aim to influence people's choices in relation to substituting car travel with more-sustainable transportation modes, with a special focus on micromobility and public transport.

4. Results: method development and application

This section presents the outcomes of applying the context-specific method of generating pathways to the rural context of three Skaraborg municipalities.

4.1. Data and literature review – Phase 1: conceptual pathways

Initiating this study with a literature review resulted in the identification of the most-common non-fossil fuel solutions, which this study defined as conceptual pathways.

According to the search method detailed in Section 2, a total of 369 articles was found. Skimming through the abstracts, results, and conclusion sections of each article reduced the number to 52 relevant articles. Each of these 52 articles was analyzed, which allowed for the categorization of the articles into different non-fossil road fuel pathways or solutions.

Among the publications, fleet electrification, public transport services, and biofuels (including both liquid biofuels and biogas) were often presented as the solutions that are most likely to meet road transport carbon emissions reduction goals. Hydrogen fuel, micromobility, Mobility as a Service (MaaS), and autonomous vehicles were also suggested, albeit to a lesser extent, as good complementary strategies for road transport decarbonization. These non-fossil fuel and mobility road transport solutions were transcribed into seven conceptual pathways that focus on solutions, as listed in Table 1.

In the next step, the conceptual pathways that were regarded as feasible for implementation in the interviewed municipalities were identified.

4.2. Participation interaction

The feasibility levels of the seven identified conceptual pathways were evaluated according to the local energy system perspective and the local specifications of each participating municipality. To achieve a better local perspective, contact was established with officials in the three selected municipalities, specifically with one traffic planner [140], one environmental strategist and municipal ecologist[1] [141], and one city planner [142].

4.2.1. Municipal officials' participation – Phase 1

The semi-structured interviews revealed that the participating municipalities shared a common commitment towards the regionally initiated climate goal, Klimat30. During this stage, the researchers and municipal officials discussed qualitatively the local feasibility and thus, the implementation of each of the seven conceptual pathways (i.e., how well a given conceptual pathway could fit into the local context of the participating municipality). This discussion occurred in a context-specific manner, targeting the specific characteristics of the local energy system of each municipality. The municipal officials' semi-structured interviews responses are thoroughly presented in the Appendix (see Table C 1).

The preferences stated by the interviewees were supported by an analysis of official municipal documents. Merging the information extracted from these two sources resulted, as depicted in Table 2, in the identification of both opportunities (enablers) and challenges (gaps) to implementation. These factors were in line with the municipalities' actions with respect to their climate agendas. The municipalities already support the implementation of some of the identified conceptual pathways, through applying incentives for their adoption (defined herein as opportunities). In terms of fleet electrification, the municipalities are already identifying locations for further investments in charging stations. Similarly, the municipalities offer personalized technical support to those who intend to become prosumers (i.e., someone who both produces and consumes energy [143]), by installing a system that integrates solar panels with an Electric Vehicle (EV) charger. Due to the uncertainty in relation to the burden that fleet electrification will impose on the electric grid, municipalities share a commitment to becoming self-sufficient in terms of electricity generation, by using locally produced sources, such as VRES and co-generation of biomass-based electricity and heat. Biofuels, which can be used in existing Internal Combustion Engine Vehicles (ICEVs), were also spoken about in positive terms by the municipal officials, who stated their intention to invest further in biofuel-based refueling stations. Specifically, municipalities reflected on the role that Hydrotreated Vegetable Oil (HVO), which is already used for agricultural machinery at the local level, could play as a road fuel. Public transport was also discussed by the municipalities, as it could be an important contributor to meeting climate goals. Moreover, municipalities presented plans to replace their municipality-owned service vehicles, including both vans and mini-buses, to vehicles that run on only biofuels and electricity, as well as plans to restructure these offerings as more-flexible, on-demand services. To guarantee access to public transport services in the most remote and rural places, municipalities emphasized the importance of establishing and investing in smart connections, where micromobility could be used for the first and last mile of transport. As an example, the municipalities shared their plan to place bike lockers at the primary public transport hub. These lockers would be available free of charge for those who presented a public transport valid ticket.

The main challenges experienced by the participating municipalities regarding the implementation of the pathways are strongly related to the culture and the attitude that has normalized car ownership, for example free municipal parking. The lifetimes of existing cars also add to the inertia of the transition, meaning that even though there is increased adoption of EVs, biofuel, and hydrogen cars, the remaining fossil fuel-powered cars will still be driven for some time to come. Moreover, municipalities expressed concern regarding the effects that electrification of the fleet might have on the electricity grid. Such effects were discussed both in terms of the requirement for expansion of the current grid and uncertainty regarding the carbon content of the added electricity. In fact, the municipalities, due to their proximity to a military airport, could in the future be constrained from investing in wind power plants. Another concern was that public transport services are regulated at the regional level and often lack an appreciation of local travel demands, often leading to these services being poorly managed. Therefore, municipal officials expressed some doubts regarding the role that public transport services could play in the future, rural, carbon-free road transport systems.

The three municipalities described themselves as municipalities in which the inhabitants commute between each other, meaning that inter-municipal transport represents the highest share of the transport

[1] According to the interviewee, the role of the municipal ecologist involves fieldwork aimed at collecting and analyzing data in the environmental context linked to related topics, such as climate, energy, forest degradation, and water management.

Table 1
Most-commonly reported road transport decarbonization solutions, according to the peer-reviewed scientific literature analyzed in this study. Some of the studies identify more than one possible road transport decarbonization solution. The term "local" stands for local energy systems. MaaS, Mobility as a Service.

Road transport decarbonization pathways/solutions	Number of studies	Number of studies with a local/rural focus	References
Fleet electrification	31	11	[28–30,36–39,92–115]
Public transport service	23	11	[27,28,30,31,39,41–43,107,110,114,116–127]
Biofuel	8	3	[29,107,115,128–132]
Hydrogen	10	3	[29,96,97,99,104,105,107,130,131,133]
Micromobility	9	3	[28,30,39,127,134–138]
MaaS	6	4	[28,29,31,42,114,134]
Autonomous vehicles	5	3	[28,29,40,120,139]

demand. This resulted in the municipalities coinciding in their perceptions of the feasibility of the conceptual pathways, as well as in the identification of implementation factors. Thus, the same conceptual pathways were identified for the three municipalities as being feasible for implementation at the local level.

4.2.2. *Feasible conceptual pathways*

As illustrated in Fig. 8, due to the municipalities' Year 2030 climate goals, the municipal officials were in favor of the conceptual pathways focusing on mature technologies, such as fleet electrification, public transport services, and biofuels. The implementation potential of these pathways was positively evaluated, considering that the opportunity to meet the different local energy systems demands was qualitatively adjudged to be greater than the implementation-related challenges (e.g., low technology and infrastructure readiness, lack of regulation, financial barriers, and stakeholder disengagement). Furthermore, the three conceptual pathways that were positively evaluated all depended on mature technologies, thereby offering shorter implementation times, which is an important requirement to meet short-term goals, such as the municipalities' Year 2030 climate goals. The other four conceptual pathways, due to their uncertain short-term applicability, were rejected by the officials and were not considered in the later stages.

Through discussions between the researchers and municipal officials, the factors that influence the implementation potentials of the positively evaluated pathways were explored further. These factors were understood by the municipalities to depend on different socio-economic, technical, and regulatory internal and external factors. Accordingly, four internal factors were identified, namely the abilities of the municipalities to: (i) establish their own CO_2 goals; (ii) constrain the use of fossil fuels within their borders; (iii) decide on the flexibility (trade) of local energy resources (both bio-sources and VRES); and (iv) restrict the supply of a specific transport mode, through specific bans. In addition, four external factors were identified over which the municipalities do not have control but to which they must adapt, namely: (i) carbon tax values; (ii) electricity prices; (iii) fossil fuel prices; and (iv) the total transport demand.

4.3. *Pathways generation*

The three conceptual pathways deemed to be feasible, which focus on fleet electrification, public transport services, and biofuels, were thereafter validated by a literature review.

4.3.1. *Cross-sectoral understanding*

4.3.1.1. Literature review – Phase 2. This second literature review was targeted at understanding the cross-sectoral impacts that these pathways, if implemented at the local level, could have on other parts of the local energy system (including both local heating and electricity distribution). Six studies were identified that address what cross-sectoral impact of road transport decarbonization might have on the overall structure of local energy systems. The resulting literature thoroughly discussed the cross-sectoral impact of passenger car electrification, underscoring the importance of these vehicles as flexible providers and grid stability contributors to the whole electricity sector. No study was found to delve into the cross-sectoral implications of biofuels and public transport. Studies on public transport often advocate for its electrification and thus, its cross-sectoral impact was inferred to mirror those identified in the literature for private car electrification. Additionally, the cross-sectoral impact of road transport strategies reliant on biofuels was deduced from interpreting general studies on bioenergy. Both the second literature review outcome and the bioenergy studies added are presented in the Appendix (see Table C 2).

4.3.1.2. Qualitative reference energy system. Overall, a second literature review added a deeper local-regional dimension to the present study, as depicted by the RES in Fig. 9. A RES that specifically targets the local energy system context of the municipalities represents a valuable qualitative asset. The RES confers a cross-sectoral perspective, which facilitates the identification of system integrators. Local resources that can be allocated to substitute fossil fuels in different parts of the local energy system are defined as system integrators (e.g., biomass can be used for heating purposes, for generating electricity, and to produce biofuels for transport). In the present study, biomass, biogas, and VRES were identified as system integrators, contributing to either synergies or competitions within the different parts of the local energy system. Biomass could be applied in all three sub-local energy systems considered in this study, while biogas could either fuel road transport or supply the heating demand. VRES, as electricity sources, could be used to supply household and commercial electricity demands, meet the fleet electrification demand, and produce hydrogen for use in fuel cells.

4.3.1.3. System pathways. Generating a local RES resulted in a detailed and descriptive cross-sectoral representation of each of the different feasible conceptual pathways. This led to the identification of three systemic pathways, which highlighted that the road decarbonization pathways rely on local energy sources. Yet, the availability of these local energy sources (e.g., biomass, biogas, and electricity from VRES) is a limiting factor for pathway implementation because the same sources can be used in more than one energy sector. However, when the demand for these local resources exceeds the supply, cross-sectoral competition can lead to innovative synergies within the local energy system. Ravi et al. [144] have described vehicle-to-grid (V2G) as an example of such a synergy. V2G stores surplus electricity and stabilizes the grid during peaks in demand by discharging electricity back to the grid during these periods. Such a synergy not only mitigates the challenges associated with the intermittency of an electricity grid with high shares of VRES, but also promotes more-sustainable and more-cost-effective road transport.

4.3.2. *Municipal officials' participation – Phase 2*

The systemic pathways were returned to the Participatory Interaction Stage, Phase 2 for re-evaluation by the officials from the three participating municipalities. During this second-phase meetings ([145–147]), the officials were presented with the systematic pathways for fleet electrification, public transport services, and biofuels. Moreover, the officials were informed about the cross-sectoral implications that the implementation of these pathways could have on parts of the

Table 2
Identification of implementation factors for the conceptual pathways, in relation to opportunities and challenges, according to the actors' stated preferences (interview outcomes) and the data in published and official municipal documents. In the column labeled "Klimat30", the symbol "O" indicates that the municipality has committed to the Klimat30 agreement. EVs, Electric vehicles; HVO, hydrotreated vegetable oil (biodiesel).

Municipality	Role	Klimat30	Conceptual pathways implementation factors	
			Opportunities	Challenges
A	Traffic Planner	O	• Prevalence of EVs with full municipality support. • Municipality's service cars run totally on locally supplied biofuel. • Municipality buses are fully electric.	• Culture and attitudes regarding owning a car. • Car lifetime. • Uncertainty regarding the electricity grid. • Unreliable and non-local regulated public transport.
B	Environmental Strategist & Municipal Ecologist	O	• Increase in numbers of EVs with full municipality support. • Increase in numbers of biofuel vehicles, with a special focus on HVO as fuel. • Refueling station for biogas vehicles. • Flexible public transport services.	• Culture and attitudes regarding owning a car. • Free parking. • Need for investment in public charging infrastructure. • Lack of legislation to limit the use of personal cars (e.g., in the municipality center, personal cars are still free to drive, and the parking is free of charge). • Unreliable and non-local regulated public transport.
C	City Planner	O	• Prevalence of biofuel vehicles fully locally supplied. • Increase in numbers of EVs with full. municipality support. • Fully electric public transport.	• Late signing of the *Klimat30* agreement (2021) demands a quicker fossil fuel-free transition to meet the set goals, as compared to other municipalities. • Uncertainty as to how to monitor the goals. • Uncertainty regarding the electricity grid. • Unreliable and non-local regulated public transport.

energy system other than road transport. From the overview described by the researcher, the officials were again asked to give their opinions as to the feasibility of the systemic pathways from a local perspective, taking into account factors such as mobility patterns, other local energy demand profiles, and national climate actions. As in Phase 1, the officials were encouraged to add information that could broaden the perspective regarding the implementation potentials of the discussed pathways. At this stage, the three participating municipalities agreed on the role that road tourism demand could play in meeting the *Klimat30* goal. Accordingly, the officials suggested adding a pathway that focused on the impact that a car-free tourism demand could have on the decarbonization of the overall municipality road transport system.

4.3.3. Identified pathways

This final feasibility assessment resulted in the generation of five rural road transport decarbonization pathways ("Identified Pathways"), which are presented in Table 3. Despite all the identified pathways being aligned with region Västra Götaland's goal and thus compatible with achieving carbon neutrality by Year 2030, their feasibilities revealed variability with regards to the different internal and external factors identified in Section 4.2. In addition, the identified pathways focused on the, according to municipal officials and based on projects already in place, most-prioritized aspects, such as fleet electrification challenges, biofuel local potential, deregulation of public transport, and increasing the flow of tourists into these municipalities.

Pathway 1, the *Base* pathway, reflects today's situation (Year 2019 was considered as the base year). This is the starting point, and both historic and current trends (transport demand in passenger-km, as well as electricity and fuel prices), as default assumptions, are projected over the time horizon given by Klimat30 (2030). As a baseline and thus, a reference point for the other identified pathways, the base pathway answers the question as to *what happens if today's trends are extrapolated to the future*.

Pathway 2, the *Self-sufficiency Electricity* pathway, assumes that fleet electrification faces challenges when implemented in areas with high-level dependency on cars, considering the current high electricity price, electricity grid expansion requirement, uncertain carbon intensity of marginal electricity, and the inadequate supply of charging infrastructure. In parallel, most municipalities aim to become self-sufficient in terms of electricity generation, by means of VRES (wind and solar) and the co-generation of biomass-based electricity and heat. In this pathway, from the average annual perspective, a given municipality is fully supplied by local energy resources regarding the stationary energy sector. Bridging the gap between producing electricity locally and fleet electrification (a synergy) can increase awareness about electricity use, resulting in a more-flexible, secure, and efficient distribution of electricity. Fleet electrification, when associated with smart charging (i.e., a strategy that optimizes charging events by optimizing energy use, minimizing the costs, and ensuring the stability of the electricity grid [148]) is assumed to be a flexible option that reduces the grid's load fluctuations, as well as its needs for storage or other demand-side management options [49–52,92–97]. Furthermore, the presented synergy can lower the need for trade with the regional electricity distribution grid. Therefore, dismissing the need for regional electricity trade is expected to decrease the marginal cost of electricity, at the level of a municipality. The main reason for this is that, if one is simply meeting local electricity demands, less generation capacity will need to be installed, which means that power plants with lower running costs, such as those using VRES, will be on the margin [51,149]. Thus, this pathway evaluates *how rural road transport decarbonization can benefit from the local availability of VRES*. The local availability of VRES will, consequently, increase the value of these sources in the regional and national markets.

Pathway 3, called the *Bio-locked* pathway, accords with Ahlgren et al. [48] and Scarlat et al. [150] who identified biomass, liquid biofuels, and biogas as important system integrators that, due to their typical local availability, can contribute to local development and the local economy. Thus, these bio-sources may play important roles in achieving the transport climate goals from a local perspective. Nonetheless, the extent to which bio-sources can supply transport depends not only on advances in conversion technologies and on the efficiency and feasibility of other fuel sources, but also (and predominantly) on competing demands for bioenergy and land. The diverse applicability of bio-sources coupled with their limited availability highlights the need to optimize the use of the energy potential of these sources, allocating them effectively within the different parts of the energy system. The need to prioritize where to use the limited sources suggests that transport decarbonization should be addressed in the context of the local energy system (including both local district heating and electricity distribution). In this pathway, it is not possible to import biomass, liquid biofuels or biogas, meaning that municipalities can only use what is available locally. This pathway emphasizes the role of local bio-energy sources by understanding *what happens if the availability of these sources is constrained*. This pathway will test the local/regional sector-coupling boundaries.

Pathway 4 focuses on *Flexible Public Transport* and was developed according to the travel demand that, in this study, is defined as inter-

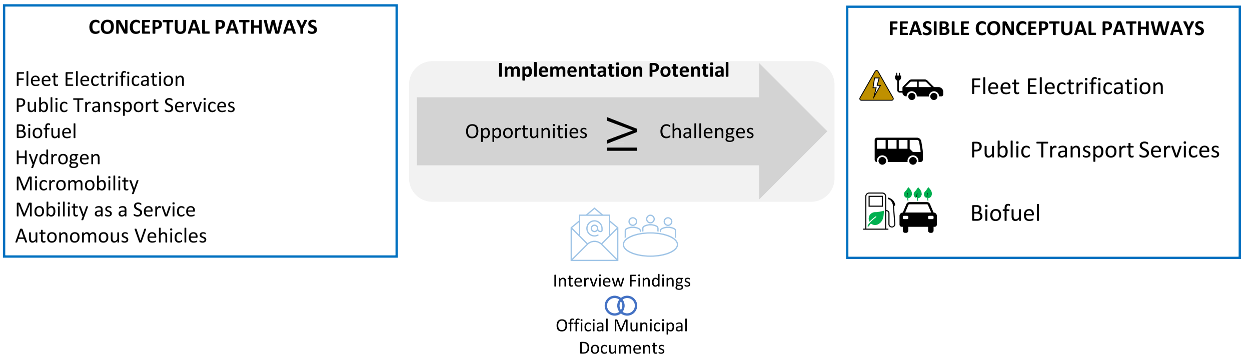

Fig. 8. The three conceptual pathways, which focus on fleet electrification, public transport services, and biofuels, were positively evaluated regarding their local feasibility. This result is a direct outcome of the Participatory Interaction – Phase 1, which assessed the local implementation potential of each conceptual pathway in terms of opportunities and associated challenges.

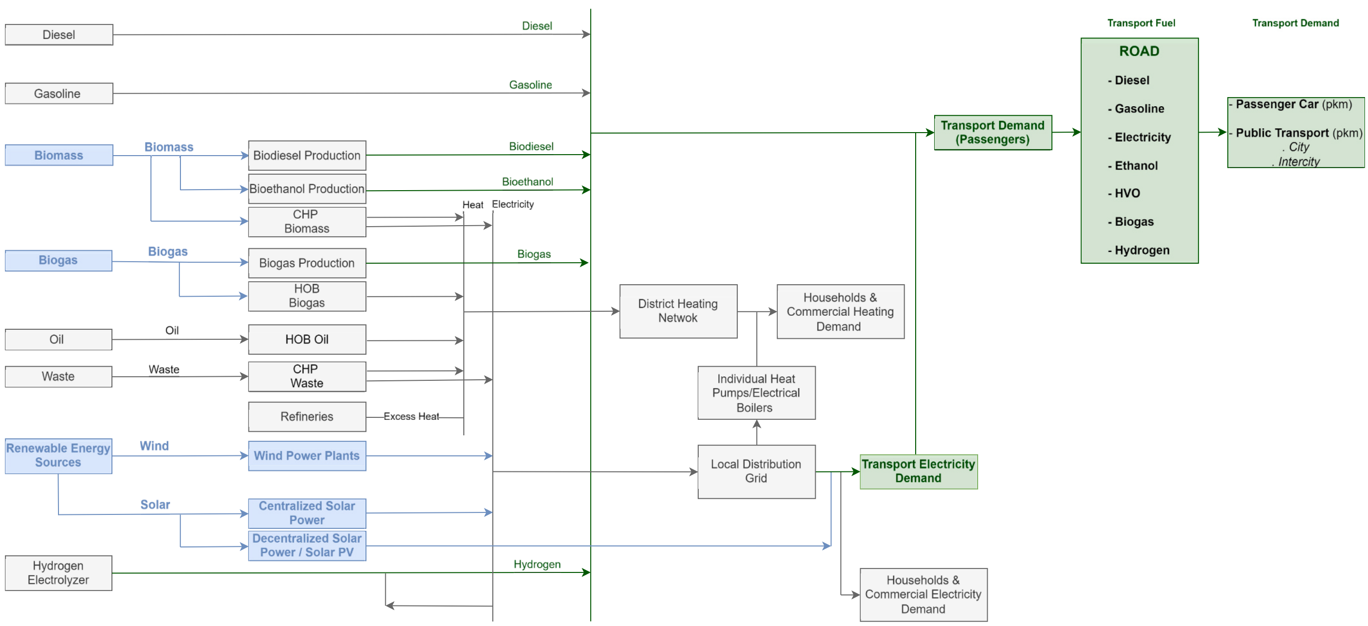

Fig. 9. Qualitative local reference energy system (RES) developed according to the findings from the semi-structured interviews and the Literature Review – Phase 2. The focus of this RES is to convey how different sub-local energy systems are coupled, facilitating the identification of system integrators, with special emphasis on transport, district heating, and electricity. The blue boxes identify the system integrators of specific interest for this study – biomass, biogas, and VRES. The green boxes represent local energy system parameters related to road transport, from the supply perspective (different fuels) to end-users' demands. CHP, Combined heat and power; HOB, heat-only boiler; HVO, hydrotreated vegetable oil (biodiesel); VRES, variable renewable energy sources. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Pathways matrix. The symbol "O" corresponds to the internal and external factors that are assumed to impact a pathway when it is integrated into the local context. In contrast, the symbol "X" represents internal and external factors that are assumed not to influence a given pathway.

Pathway	Internal factors					External factors			
	CO_2 goal	Fossil fuel ban	Local energy sources flexibility - Trade		Specific transport mode supply ban	Carbon tax	Electricity price	Fossil fuel price	Total transport demand
			Bio	VRESs					
1. Base	O	X	O	O	X	O	O	O	O
2. Self-sufficiency Electricity	O	X	O	X	X	O	O	O	O
3. Bio-locked	O	X	X	O	X	O	O	O	O
4. Flexible Public Transport	O	X	O	O	O	O	O	O	O
5. Green Tourism	O	O	O	O	O	O	O	O	O

municipal. The adoption and acceptance of public transport services in rural areas might benefit from their typical inter-municipal travel demands. However, public transport providers, as argued by different actors, when operating at the rural level find it difficult to offer a service that fits the mobility needs and expectations of the different citizens at a reasonable cost [116–118]. Subsequently, this pathway focuses on the broad implementation of public transport services in rural areas. In particular, it assesses *how structured, integrated, and on-demand public transport planning can improve the passenger experience* in terms of the value of travel time, cost, and accessibility. By doing so, this pathway looks at how public transport can reduce the travel demand of cars and, thereby, lower the environmental impact of individual transport modes.

Pathway 5, termed the *Green Tourism* pathway, considers the fact that the municipalities under study are characterized as tourist destinations. Thus, this study identifies a pathway that assesses a *tourism transport demand that is supplied exclusively by green transport modes*. This will enable visitors to travel to, from, and within the municipalities in a more-sustainable way, contributing to branding the destination as sustainable, which in turn may increase attractiveness as a tourist destination. According to this perspective, the transport demand of tourism is constrained so as to be exclusively supplied by either public transport (buses) or micromobility within the city borders. As many tourists can be expected to keep traveling to and from the municipalities with their own cars, it is important to consider strategies that constrain the use of individual cars within municipality boards, while incentivizing the usage of public transport and micromobility. One such strategy could be to restrict car driving in the municipal center to residents, while coupling it with a “park and ride” policy (see e.g., [151,152]). Accordingly, non-residents could find free parking facilities at the municipality’s borders. These facilities would be connected to the municipal center by well-established public transport services and a micromobility infrastructure.

4.3.3.1. Qualitative performance assessment. The qualitative performances of the identified pathways were evaluated according to different criteria through a qualitative performance assessment that applied a “traffic light” color scheme, as presented in Fig. 10. The criteria were selected during the Participatory Interaction Stage. Accordingly, the following five criteria were selected in a collaboration between the research team and municipal officials: (i) Economic Impact; (ii) Local Emissions; (iii) Transport Mode Municipal Availability; (iv) Refueling and Charging Infrastructure Availability; and (v) Trip Planning.

The *Economic Impact* criterion evaluates how each of the identified pathways can be economically perceived by the different actors, i.e., car owner, municipality, and region. In particular, for each of the identified pathways, this criterion assesses which types (i.e., transport and infrastructure) of investments are needed. From the car owner’s perspective, the *Self-sufficiency Electricity* pathway is perceived as an expense, as it demands an investment in BEVs, for the ones that do not yet own one. Furthermore, this pathway expects that the transition into BEVs will go hand in hand with an increase in prosumers, since BEV-owners often install solar panels and home chargers. The *Bio-locked* pathway promotes the use of biofuels motivating the use of existing ICEVs, not requiring car owners to invest in new cars. The *Flexible Public Transport* and *Green Tourism* pathways support reductions in car use, decreasing the need for refueling, as well as the operation and maintenance costs of owning a private car.

From the municipal and regional perspectives, all the identified pathways, with the exception of the *Flexible Public Transport* (municipality) and *Green Tourism* (region) pathways, are perceived as an expense. The main reason for this is that investments in infrastructure will need to be made at the municipal and regional levels, to support the implementation of the identified pathways. In both the *Self-sufficiency Electricity* and *Bio-locked* pathways, a municipality (but also the whole region) due to the inter-municipal demands of the participating municipalities, will need to invest in public charging, as well as in liquid biofuel and biogas refueling stations. As public transport services are regulated at the regional level, all the costs associated with improving these services at the local level become the responsibility of the region. In contrast, in the *Green Tourism* pathway, a municipality will be responsible for investing in car parking facilities, as well as for providing reliable public transport and micromobility connections between these facilities and the municipal center.

The *Local Emission* criterion evaluates the potential impacts that each of the identified pathways can have on the local air quality. This criterion looks at the local emissions generated by the transport mode(s) that each of the identified pathway favors. Accordingly, all the pathways, with the exception of the *Bio-locked* pathway, support a reduced use of ICEVs, potentially leading to a decrease in local emissions.

The *Transport Mode Municipal Availability* criterion looks at the current availability of the specific transport mode(s) that each of the identified pathway favors. The municipalities are still lacking transport alternatives to ICEVs. BEVs are still in the minority in the municipalities’ existing passenger car fleets, and there are even fewer BEVs in the municipality-owned bus fleet. Since the *Bio-locked* pathway supports the use of liquid biofuels and biogas, it is compatible with existing ICEVs. As ICEVs predominate in the existing passenger car fleet, the *Bio-locked* pathway is the only positively evaluated pathway regarding *Transport Mode Municipal Availability*.

The *Refueling and Charging Infrastructure Availability* criterion assesses the current existing refueling and charging facilities that are capable of supplying the fuels that each of the identified pathway favors. This

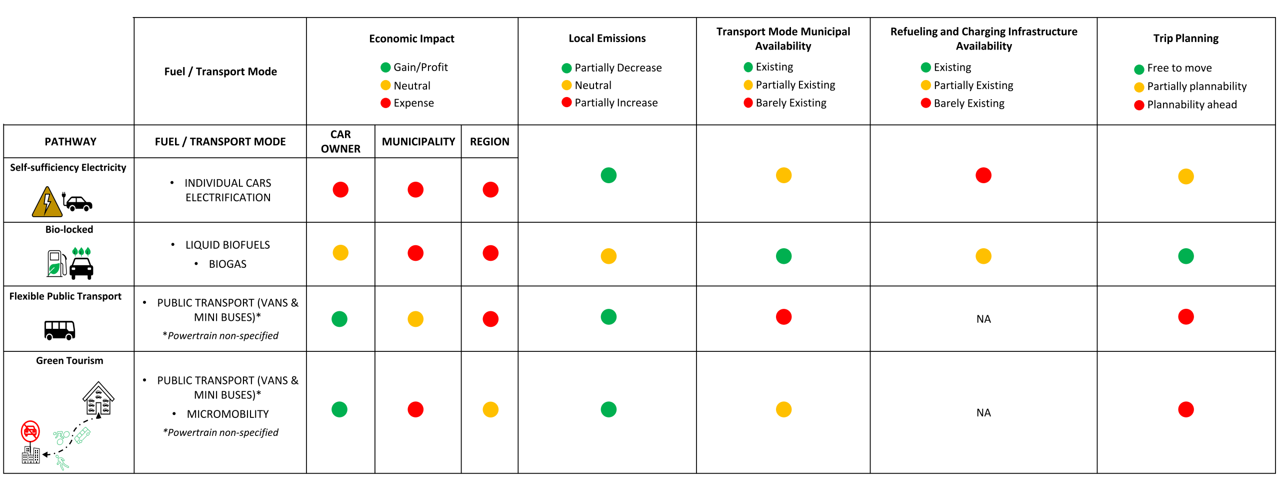

Fig. 10. Qualitative assessment criteria matrix. NA, Not applicable.

criterion was only applied to the *Self-sufficiency Electricity* and *Bio-locked* pathways and showed that despite refueling and charging facilities being already in place within the municipalities' borders, their levels of availability are still limited, especially in terms of public charging stations.

The *Trip Planning* criterion evaluates how much a trip demands to be planned, according to the specific transport mode(s) that each of the identified pathway favors. This criterion favors the pathways that support the use of private cars, as the driver can freely decide regarding a given trip itinerary and schedule. Yet, the *Self-sufficiency Electricity* pathway supports the use of BEVs, which due to their limited battery range and long charging times increase the need for trip planning. Both the *Flexible Public Transport* and *Green Tourism* pathways depend on transport modes that are managed by both the municipality and the region, which means that the trips supplied by these pathways need to be well-planned.

5. Discussion and conclusions

The aim of this study was to understand how generating pathways, if developed as a context-specific method, can support the decarbonization of rural road transport systems. Moreover, this study investigated how pathways can be generated in an iterative and co-developed manner by combining literature review findings and participatory interactions to achieve a better understanding of local energy systems. Thus, a spatial local-regional dimension and a cross-sectoral perspective were added to the process of generating pathways.

The context-specific method was applied to three Swedish rural municipalities, and five decarbonization road transport pathways were generated. These pathways suggest that fleet electrification, bio-source inflexibility, flexible public transport services, and non-carbon tourism travel demands are promising measures to meet local emissions reduction targets in line with global climate targets. As a validation metric, this study conducted a qualitative performance assessment for each identified pathway. This assessment evaluated the economic, environmental, and logistical aspects of local implementation of each identified pathway, providing insights into their local feasibility and impacts. In addition, the identified pathways revealed the system integrator role that local resources, such as biomass, biogas, and VRES, play. Identifying these system integrators revealed the implications of each of the five identified pathways for all parts of local energy systems. These implications are in the form of either synergies or competition for these local resources.

The qualitative performance assessment of the identified pathways facilitated the ranking of the relative performance of the identified pathways, concluding that: (i) the *Self-sufficiency Electricity* pathway can contribute positively to decreasing local emissions; (ii) the *Bio-locked* pathway benefits car owners, by allowing them to continue driving their ICEVs and freely deciding over their trips; and (iii) both the *Flexible Public Transport* and *Green Tourism* pathways decrease the travel demand that has to be met by private cars, thereby reducing car usage (and consequently, the fueling demand), so as to reduce local emissions. Thus, depending on what aspects the municipalities prioritize, different pathways are judged to be the most attractive. However, all the pathways have the potential to contribute to the decarbonization of their road transport systems.

5.1. Comparison with previous studies

In line with the existing studies on rural road transport decarbonization, the identified pathways also underscore the effectiveness of private cars fleet electrification and public transport services as low-carbon solutions.

Specifically, this study agrees with Xu et al. [36] in highlighting private car fleet electrification, particularly when coupled with self-sufficiency electricity production, as a means to reduce fuel consumption (as also noted by Suttakul et al. [37]) and provide flexibility to the electricity grid. Emphasizing the importance of combining fleet electrification with smart-charging strategies such as V2G, the present study is consistent with Walters et al. [40]. However, while acknowledging the benefits of fleet electrification, this study, echoing Nilsson et al. [38], further reflects that the local feasibility of such a low-carbon solution hinges on municipal and regional economic support for charging infrastructure investment. Similarly, in line with Köhler et al. [39], this study affirms fleet electrification as an effective low-carbon solution for rural areas, aligning with the socio-cultural tendencies of these regions that heavily rely on private cars.

While fleet electrification is pivotal for rural road transport decarbonization, complementing it with other low-carbon solutions that reduce societal car dependency, such as public transport, is essential. However, the present study acknowledges, as Bell et al. [41], also describes, the challenges in rural areas, including the lack of fair and reliable public transport services. These challenges, as identified through semi-interviews and discussions with municipal officials, stem from the unbalanced management of services at the regional level, often favoring urban areas over rural ones. Aligning with Li et al. [42] and Enoch et al. [43], this study supports that the effective adoption of public transport services in rural areas requires a comprehensive understanding and consideration of local travel patterns and needs.

This study expands on existing research by examining alternative fuels such as liquid biofuels and biogas, as well as changes in travel behavior, as potential low-carbon road transport solutions for rural areas. Specifically, it emphasizes the transitional role that alternative fuels can play in reducing road transport emissions without the need for investing in new vehicles. Additionally, the study argues that the effective allocation of these resources within the local energy system can contribute to local development and the economy. Changes in travel behavior, such as limiting driving in city centers, similar to measures implemented in urban areas, can also aid in decarbonizing road transport in rural areas. However, implementing such measures requires support from municipal governments to establish suitable regulations. More than limiting the driving of private cars, such regulations are needed to further ensure travel quality and reliability of alternative transport means such as public transport and micromobility.

5.2. General reflections

The existing research on road transport decarbonization often adopts a national perspective, relying on an aggregated understanding, by means of national weighted average values and travel patterns, that tend to overvalue urban areas. This approach overlooks the nuanced understanding required for effective transition at the local level. This study serves as a critique of this approach, advocating for a tailored approach to road transport decarbonization that considers the specific context of each transition. The effectiveness of such a transition relies on the alignment of low-carbon solutions with local behavior and socio-geographic characteristics.

Overall, this study identifies some feasible decarbonization road transport pathways to be implemented at the local level and also suggests that current national and regional climate goals can benefit from considering the contexts of municipalities, so as to contribute to a more inclusive and resilient transition towards a decarbonized road transport system. In particular, it is important to consider that: (i) municipalities' contributions towards climate goals can benefit from the availability of local resources that are typically difficult to export; and (ii) the economic potential of municipalities to make investments in new technologies and infrastructure is limited. Such an imbalance supports the idea that municipalities prioritize investments differently, so road transport decarbonization pathways could also be differently prioritized.

While this study is primarily focused on the Swedish context, the method developed for generating road transport pathways yields results that can convey a universal message to an international audience and diverse stakeholders. This method can effectively address various dimensions of not only road transport decarbonization but also other types of energy transitions. Specifically, this study makes a practical contribution by incorporating a local perspective and avoiding the standardization of national actions at the local level across diverse municipalities. This perspective offers a new insight for national and regional policymakers, highlighting the complexity beyond a "one-size-fits-all" strategy.

5.3. Limitations and future work

The different stages of the developed method are associated with specific uncertainties. This study was initiated with a literature review, which limited the scope to the selection process and search operators utilized. To increase the coverage, the research team conducted complementary literature reviews with only a few specific search commands. The literature review stage and its findings were later discussed with municipal officials, using a participatory approach. Yet, the participatory interactions of the officials, due to their ambiguity, challenged the extrapolation of the analysis of the stated preferences into a conceptual and quantitative representation. In the same way, as different people may not express the same idea in the same way, processing information from semi-structured interviews can challenge the consistency of the outcomes of the discussions between the researchers and municipal officials. To better tackle the above-described limitations, the context-specific method of generating pathways was co-developed by establishing an iterative complementing loop between the different phases of the literature review and the participatory interactions of the municipal officials. Iteratively merging the findings between the stages mitigated: (i) the literature review limitations in relation to understanding that some non-carbon transport solutions might not be compatible with the current social, political, and economic contexts; and (ii) the participatory interactions and stakeholders' difficulties in dealing with uncertainties in the long-term.

In this study, the interviewees in each municipality had different roles. This heterogeneity of the roles of the participating municipal officials could be argued as being a limiting factor in relation to the robustness of the identified pathways. Still, the three participating municipalities were identified as commuting municipalities, influencing each other's mobility patterns. Accordingly, and owing to the inter-municipal transport demand, the heterogeneity of officials' roles broadened the perspectives, facilitating a thorough understanding of the levels of effectiveness of the identified pathways.

The developed method of generating pathways was applied to the context of three Swedish rural municipalities, resulting in five road transport pathways. It is important to note that these pathways are not projections but are rather explorative of multiple decarbonization road transport futures that could feasibly be implemented in the considered rural areas. In addition, the five pathways identified in this study are both technology-restricted abatement and transformative pathways, entailing marginal changes. Also, important to note is that the identified pathways were specifically tailored to the rural context of the participating municipalities, so the marginal adjustments may well suit their Year 2030 (short-term) goals. However, such adjustments may not be sufficient when assessing the long-term national goals, meaning that the fuel or mobility technologies supported by each of the identified pathways can play an important transitional role, but might not be part of the long-term, fossil-free road transport plan.

Although the pathways were generated through a context-specific process, the same pathways were identified for the three participating municipalities. This can be explained as follows. First, the three municipalities were revealed to be very similar in terms of the scope of this study. In particular, the three municipalities were found to be aligned in terms of local resources availability and cross-sectoral linkages, while experiencing the same opportunities and challenges with regards to their road decarbonization efforts. Furthermore, the participating municipalities were characterized as having commuting between each other. Thus, identifying the same pathways suggests that different municipalities' goals and actions can be supported if they act in harmony according to regional and collaborative perspectives. Rural road transport decarbonization, as with any other local energy transition, can benefit from coordination, cooperation, and knowledge exchange between commuting municipalities. Therefore, this study also highlights generating pathways that can offer more context-personalized support towards the decarbonization of not only rural road transport systems, but also any type of energy transition at a local level.

It is important also to note that the identified pathways were not quantitatively validated, which is something that needs to be done in the future work by, for example, incorporating the pathways into cost-minimizing energy systems modeling.

CRediT authorship contribution statement

Maria de Oliveira Laurin: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sujeetha Selvakkumaran:** Writing – review & editing, Supervision. **Erik O. Ahlgren:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Maria Grahn:** Methodology, Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgments

The authors acknowledge the financial support from the Sustainable Mobility Rural and Urban Transport (SMaRT) project, which is a Danish–Swedish collaboration funded by InterReg Öresund-Kattegat-Skagerrak. The authors are grateful to the interviewees for their contributions to this study.

Appendix A. Additional method considerations

A.1. Semi-structured interview questionnaire

1. Please tell me what is your role in Skaraborg's municipalities?

- How many years have you been working in this role?
- What is your experience in (local) energy systems-related issues and planning?
  - o Do you have experience with any local energy system in particular? (E.g., district heating, electricity, or transport.)

- What is your responsibility regarding the municipality's energy management and planning?
  - o Do you have experience regarding any local energy system managing and planning in particular? (E.g. district heating, electricity, or transport.)

2. What are your municipality's local energy system goals regarding climate change mitigation (emission reduction – carbon neutrality)?

- Are these goals in balance with the national and regional goals?
- How do these goals influence or will influence the overall municipal energy planning structure?
- What are the major challenges and problems in achieving these goals? According to your experience, do you think that these goals are achievable?
- Are you aware/do you know what are the climate targets for the different local energy systems? (E.g., district heating, electricity, or transport.)
- Is there any formally written and approved document that clearly states which are the municipality's climate goals and what are the different pathways/solutions to achieve them?

3. Can you explain how municipal energy systems are structured/managed?

- District heating:
  - o Does your municipality have district heating?
  - o How does district heating work in your municipality?
    - ▪ What is the main fuel that is supplying your district heating system?
    - ▪ Is the district heating fully locally supplied?
  - o Do you have local resources (e.g., biomass and biogas) that are already supplying (or in the future capable to supply) local heat utilities? If yes, what are they?
  - o Are there different demand and supply peaks between summer and winter (seasonal different trends)?
  - o Are the local district heating decarbonization goals and, consequently, challenges, included in the municipality energy plan? If so, how are they considered? If not, how could they be included in future municipality environmental plans?
- Electricity:
  - o How is electricity supplied and distributed in your municipality?
  - o Is electricity regionally mainly distributed?
  - o Do you have local resources (e.g., biomass and biogas) that are already supplying (or in the future capable to supply) local heat utilities? If yes, what are they?
  - o Are there seasonal different trends (summer versus winter) in terms of electricity demand but also supply?
  - o Availability of local resources has been resulting in an increasing trend of municipalities aiming to become electricity supply self-sufficient, by the means of wind power, co-generation biomass, and to some extent, solar:
    - ▪ Does your municipality experience the same trend?
    - ▪ What is the potential of electricity being fully locally supplied? Do you have local electricity generation utilities? If so, could you describe them?
  - o Are the local electricity system decarbonization goals and, consequently, challenges, included in the municipality energy plan? If so, how are they considered? If not, how could they be included in future municipality environmental plans?
- Transport (passenger modes):
  - o What does the transport demand look like in your municipality?
  - o What is the predominant transport mode (e.g., private cars, public transportation, bike…)(and in the case of being a motorized mode, what is the main fuel?)?
  - o Do you have local resources (e.g., biomass, biogas, and hydrogen) that are already supplying (or in the future capable to supply) local transport systems? If yes, what are they?
  - o Are there seasonal different trends (summer versus winter) and week trends (weekdays versus weekends) in terms of transport demand but also the transport modes used?
  - o Do you think that local transport decarbonization challenges are included in the municipality energy plan? If so, how are they considered? And if not, how could they be included in future municipality environmental plans?
- Do you know how the different local energy systems – district heating, electricity, and transport – are connected?:
  - o What does the interaction between these different local energy systems look like?
  - o Is there competition or synergy between the different local energy systems?
  - o How does this cross-sectoral interaction impact the local energy systems (district heating, electricity, and transport) supply patterns and capacity
- Can your local resources – biogas, biomass, and hydrogen – hasten municipalities' local energy systems decarbonization?:
  - o Are these local resources more important in certain sectors than others (district heating, electricity, and transport)?
  - o Do you expect major consequences, such as competition between the different local energy systems for these resources?
- Is there any resistance – technical, political, social, and economic – to preventing the transition of municipal transport systems towards carbon-neutrality?

(*If the interviewed municipality shows an understanding of the transport sector*):

4. What is the most popular and probable transport mode (e.g., private cars, public transportation, bike…) to be chosen by the municipality's citizens to meet transport demand?

- What is the share (per capita) of owned vehicles in your municipality versus Göteborg?
- What is the major reason for, contrary to what happens in major urban centers, Skaraborg municipalities presenting such a high share of registered private-owned cars per capita? (0.59 compared to, approximately, 0.36 – Göteborg and Stockholm.)
- Does the reason behind the traveling/commuting patterns of the municipality's citizens influence their transport mode choice?

- Is the transport in your municipality typically intra-municipality or inter-municipality?
- What are the motivations of the municipality transport demand? (Is the travel demand seen as an extra/leisure need or it is a social need (e.g., job, school, and other basic social services…))?
- (Within Lidköping, Vara, Skara, Götene, Grästorp, Essunga, and Mariestad) According to your expertise/interpretation, which municipality do you think to be the main center point? Which is the most popular destination, the first choice where consumers go to satisfy their needs?

5. Non-carbon transport solutions/strategies' availability and applicability are dependent on the context – main urban centers versus non-urban areas:

- Do you think that urban non-carbon transport solutions, like electrification and public transportation (and mobility as a service and micro-mobility), have the same potential to be accepted and applied in your municipality?:
  - o If yes, what is the likelihood of these transport modes' demand increasing in the future?
    - ▪ What is the municipality's role in supporting the investment in new transport trends satisfied by electric vehicles and public transportation (and to some extent, mobility as a service and micro-mobility)?
  - o If not, why do you think that efficient urban non-carbon transport solutions, like electrification and public transportation (as well as mobility as a service and micro-mobility), are not efficiently replicable in non-urban areas?
- How is the municipality dialogue with transport consumers and how are their preferences considered and included in structuring charging and public transportation infrastructure (and mobility as a service and micro-mobility)?
- Do you have charging infrastructures available in your municipalities?:
  - o If yes, are these infrastructures capable of fully satisfying the needs of your municipality's electrical fleet?
  - o If not, does your municipalities aim to financially support new investments in charging infrastructures?
- Do you know how public transportation works in your municipality? And how is public transportation managed/regulated (regionally, nationally)?:
  - o What do you think to be the major barrier to public transportation acceptance and further expansion in this municipality?
- What is the availability, acceptance, and opportunity for/of transport decarbonized solutions, such as mobility as a service and, to some extent, micro-mobility options?:
  - o Is there any incentive from the municipality's perspective to electrify these service vehicles (e.g., taxis and renting cars) or will biofuels engines prevail over electrification?
- Which carbon-neutral solutions (e.g., strategies combined with different transport technologies and modes), according to your expertise, would provide improved mobility services, while satisfying the municipality's climate goals?:
  - o Do you think that local resources – biomass, biogas, and hydrogen – can be part of these solutions and hence hastening municipalities' transport decarbonization?
  - o Is there an opportunity for alternative fuels (biogas, hydrogen, and HVO) to be included in the municipality's environmental plans? What are the drawbacks?
  - o Do alternative fuels play a more important role in your municipality's transport system decarbonization than electrification?
  - o What do you see the future of the municipal transport system look like? (In terms of technologies and demands).

A.2. Literature review – Phase 2

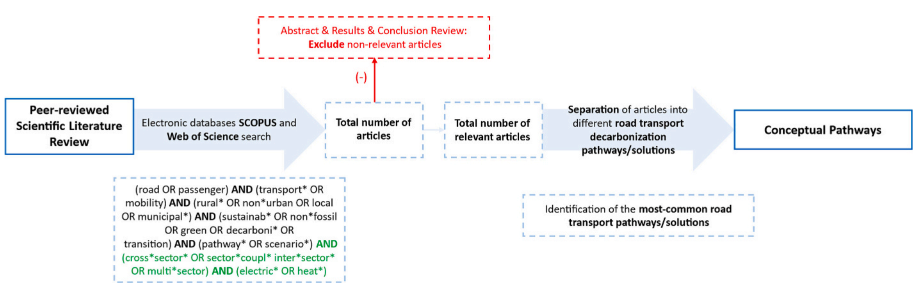

Fig. A 1. Protocol conducted in the literature review – Phase 2. The added search commands to this phase of the literature review are marked in green text. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Appendix B. Additional data

Table B 1
Daily distances traveled by individuals. Data retrieved from [86].

Municipality	Swedish association of local authorities and regions designation	Daily distance traveled per person (km)		
		Micromobility	Public transport	Car
Gothenburg	Larger city	2	10	17
Lidköping	Small city	1	6	32
Skara	Commuting municipalities near a small city	0.8	6	30
Grästorp	Commuting municipalities near a medium-sized city	1	9	35

Table B 2
Number of cars registered at the end of the Year 2019. Data retrieved from [88]. BEV, Battery-electric vehicle.

Municipality	Swedish association of local authorities and regions designation	Registered number of cars (units) powered by:						
		Gasoline	Diesel	BEV	Hybrid electric	Plug-in hybrid electric	Ethanol	Biogas
Gothenburg	Larger city	105,557	64,225	1070	5451	2387	7933	2875
Lidköping	Small city	12,572	8077	64	377	198	1066	260
Skara	Commuting municipalities near a small city	6025	3424	16	172	28	468	81
Grästorp	Commuting municipalities near a medium-sized city	1868	1371	8	28	5	175	53

Table B 3
Carbon dioxide equivalent emissions (tCO2-eq) from the use (driving) of a car according to the different types of fuels. Data retrieved from [89].

Fuel	Carbon dioxide equivalent emissions (tCO_2-eq)
Gasoline	28.2
Diesel	21.6
Electricity	6.3
Ethanol	13.1
Biogas	61.1

Appendix C. Additional results

Table C 1
A representation of the municipal officials' responses to the semi-structured interviews. In the column labeled "Klimat30", the symbol "O" indicates that the municipality has committed to the Klimat30 agreement. EV, Electric vehicle; DH, district heating; HVO, hydrotreated vegetable oil (biodiesel).

Municipality	Role	Klimat30	Semi-structured interviews responses
A	Traffic Planner	O	• "The climate goals vary depending on the different energy systems. For transport, there are different challenges for climate goals, as some goals are not accepted by people." • "For the citizens, owning a car and having free public parking is seen as a right." • "Economic perspective is the bottleneck regarding the transport transition. Cars have a lifetime meaning that they will be driven for a lot of time regardless of the transport goal." • "The transport sector is also managed at the individual level, meaning that the municipality has very little power to solve it. If in the morning someone decides to take the car instead of the bike, the municipality does not have the power to control it." • "All light-duty owned municipality cars are running on biogas and all city buses are electrical." • "EVs need support in the expansion of the electricity grid capacity. The expansion of the grid is constrained, as wind power, due to the military airport, cannot be further invested. Only investments in solar are accepted but will not be enough." • "Municipality offers support for EVs, by promising investment planning towards public charging infrastructure." • "Public transport is regionally managed, becoming a problem. There is a tendency for people to not understand the problem at the local level. Also, public transport funding at the local level is not proportional to the share of the population of a given town. It always goes for urban centers"
B	Environmental Strategist & Municipal Ecologist	O	• "There is an awareness that the municipality is following a good climate strategy regarding DH and electricity, yet there is still a lot to do in transport." • "The challenges to meeting these goals are resources, knowledge, economic factors, like investments, for instance, in charging infrastructure and legislation." • "As more rurality an area becomes, collective transport, like public transportation becomes very difficult." • "A lot of people have their own car because public transport does not work that well, for instance, in the evening buses do not run at all. Also, it is cheaper to own a car, compared to cities. In Gothenburg, it is very expensive to own a car, because of parking reasons, but in our municipality, parking is still not paid." • "HVO is becoming very important, but it is important to think about other solutions, due to the competing demand of HVO for diesel cars, lorries, and machinery." • "EVs will be more important than public transport, walking, and cycling"
C	City Planner	O	• "The municipality is very new in terms of climate goals, just in June 2021 started to include this problem in its agenda." • "Reaching the goals is not the difficult part, but yes following the system when the goals are met." • "There is a military airport nearby and thus, wind power is constrained as well as agricultural land is a limitation for solar power." • "Biogas is a big fuel in the municipality and there is already a refueling station for biogas in place." • "Most of the people living in the municipality work in other municipalities and the car becomes important. Car is so important because public transport does not work that well but also because the travel distances are rather long." • "Public transport management is not easy at the municipal level, as the region owns that power." • "The municipality aims to become self-sufficient in terms of electricity production. Not just for electricity but yes for the whole energy system perspective. Accordingly, from a self-sufficiency perspective, biogas can be more important than EV. From a bus perspective, EVs are way more fun to drive than biogas."

Table C 2
Literature review – Phase 2 outcome. The findings reflect the outcome of the peer-reviewed scientific literature analyzed and presented in Fig. A 1 and manually added relevant studies. V2G, Vehicle-to-grid.

Feasible conceptual pathways	Number of studies		Cross-sectoral effect	References
	Literature review – Phase 2 outcome	Manually added by the research team		
Fleet electrification Public transport service	6	5	Fleet electrification: • Enhances local energy usage awareness; • Can play a flexible provider role, contributing towards a secure and efficient electricity distribution; • Can be combined with smart charging strategies (V2G) as a demand-side management strategy, reducing electricity grid load fluctuations; • Decrease reliance on regional and national electricity trade; • If met locally, it reduces regional electricity trade, which, as lowering the local electricity demand, is expect to decrease the marginal cost of electricity.	[49–52,92–97,149]
Biofuel	NA	2	Biofuel (both in liquid and gaseous form): • Is locally available; • As local energy resources, contributes to the local development and economy; • Climate contribution depends on technological advancements and competing demands for bioenergy and land; • Limited availability requires an optimized allocation of its resources among the different energy systems – testing the competition of biofuel between transport, electricity, and heating systems.	[48,150]

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