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Original Research Article

Assessing Sustainability of Regional Climate and Energy Targets at Local Level for Supporting Municipalities in Navigating the Green Transition

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ABSTRACT

The European Union has implemented targets to address climate change, air pollution and increase the share of renewable energy. Local governments play a significant role in executing actions to contribute to these targets while meeting local sustainability targets. This research aims to guide the local governance by assessing the impact of implementing key energy targets from the European Union at the local level from a sustainability perspective using indicators based on sustainable development goals. An energy system optimization model is used to assess the case study of Gällivare, a municipality in Northern Sweden. The results show that localized climate and air quality targets effectively support the integration of renewable energy, improvements in energy efficiency, and reductions in final energy consumption. Air quality targets correspond carbon reduction targets and subsequently leading to the net zero emission. However, while air pollution targets help achieve 100% carbon dioxide reduction by 2050, achieving 100% reduction in air pollution requires specific air pollution targets.

KEYWORDS

Energy system optimization model, Scenario analysis, EU targets, Climate mitigation, Air pollution, Municipality.

INTRODUCTION

To limit the human-induced global warming, we must reduce the cumulative carbon dioxide (CO2) emissions and achieve net zero CO2 levels [1]. Cities across the globe consume approximately 75% of the world's primary energy [2] and is responsible for more than 70% of CO2 emissions [3]. Within the European Union (EU) cities cover 4% of the land area but house 75% of its population [4]. The European Commission has acknowledged the vital role of cities in limiting the CO2 emissions and achieving EU's climate neutrality target by 2050 [5]. Many European cities have climate mitigation targets, yet few cities are on track to meet the targets defined in the Paris agreement [6]. The EU has implemented or updated existing directives/ plan/ strategies (referred as targets henceforth) to support the Green Deal, address the emissions from the region and harmonize efforts across member states [7]. These targets include the Renewable Energy Directive, National Energy and Climate Plans, and the National Emissions Reduction Commitments Directive among others. The EU is also committed to implementing the Sustainable Development Goals (SDG) in all its policies [8].

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The literature includes studies on the varied impacts of different targets, highlighting their synergies and trade-offs. For instance, measures to reduce greenhouse gas (GHG) emissions are identified to have co-benefits in improving air quality [9] and human health [10]. The study [11] suggests that the CO2 released from direct and indirect land-use changes associated with biofuel production could outweigh the GHG reductions achieved by displacing fossil fuels. [12] emphases the need to address air pollution concerns associated with biofuel production and utilization. [13] assess the impact of EU directives on biofuel usage and sustainability, it is suggested that these policies could lead to higher emissions from indirect land use changes and increased direct emissions from transportation. [14] finds that Swedish climate policy generates substantial ancillary benefits, which, while adding to the total system costs, effectively lowers the overall expense of implementing climate policy. [15] analyzes the ancillary and co-benefits of transport policies, underscoring the necessity of firm understanding of these relationships to formulate robust urban sustainability strategies. While these studies assess different targets at different geographical levels, the impact of EU targets at the local level is not addressed. This is imperative given i) the extensive and growing body of EU targets [7], ii) the unique position of local authorities to integrate and adapt targets to their specific contexts [16] and iii) the interconnected nature of the targets [17].

This research aims to fill this gap and thereby provide improved guidance to local governance by assessing the impact of implementing EU energy targets on the sustainability of the local energy transition. It seeks to answer the questions:

1. Are the EU targets corresponding or contradictory at the local level?
2. Which technology and fuel options are considered cost-efficient from a system perspective in different scenarios?
3. What is the sustainability measured with sustainability indicators of each scenario?

The study employs an energy system optimisation model for identifying cost-optimized solutions to meet future energy related societal needs under given constraints. The model provides a technology rich representation of the local energy system, from energy supply to useful energy demand [14]. Different scenarios reflecting the EU targets are incorporated into the model and the sustainability of these scenarios is assessed using model-based sustainability indicators developed in [18]. The study focuses on Gällivare, a municipality in Northern Sweden. The study provides insights into the effectiveness of EU targets in promoting sustainability at the local level and enabling local authorities and policy makers for data-driven decision-making on sustainable energy transition.

BACKGROUND

Addressing climate change requires coordinated action at global, regional, national, and local levels [19]. While international agreements like the Paris Agreement and regional targets the EU Green Deal set overarching goals for carbon neutrality, their success hinges on effective implementation at the local level. Cities, which account for a significant share of energy consumption and emissions, play a crucial role in this transition [20]. Particularly, municipalities undergoing industrial transformation and evolving energy landscapes face greater challenges in aligning local actions with broader sustainability goals. This section briefs the case study municipality’s energy system and the key EU climate and energy targets policies.

Local energy system

Gällivare Municipality covers an area of around 16,800 sq. km. and has a population of 17,431 in 2022. The economy is heavily dependent on the mining industry, which provides the majority of employment opportunities for the local population. Gällivare is undergoing significant changes over the past decade. The town has been relocated to accommodate the increased mining activity, which has involved the demolition and movement of houses as well as the construction of new residential areas. Additionally, there is the restructuring of the ore-to-steel supply chain in Northern Sweden, to produce fossil free steel. The projects aim to leverage the availability of cheap electricity and abundant resources such as iron ore and water in the region. For example, the world's first fossil-free sponge iron production plant is under construction in Gällivare. These projects are expected to provide new job opportunities and attract other companies in the renewable energy industry to the area. The municipality is putting forth strong efforts to make Gällivare a socially sustainable place and to attract more people to the area. These factors are anticipated to influence the municipality's energy system, resulting in increased demand for energy-intensive services and products.

Gällivare, has an installed capacity of 610 MW hydropower, 121 MW wind power, and 0.16 MW solar power. The primary district heating source is a 40 MW biomass-based combined heat and power (CHP) plant. Gällivare generates the electricity and district heating to meet its demand but imports all other fuels such as biomass and transportation fuels. Industry followed by transport and residential sectors are the major energy consumers. **Figure 1** represents the energy demand per sector per fuel type (left) and electricity fuel mix (right) used to meet the demand for the year 2020. For transport sector, the passenger travel demand was 230 million passenger-km and the freight demand was 66 million ton-km in 2020. **Figure 2** shows the final energy consumption (FEC) per sector per fuel type (left) and end-use CO2 emissions (right) for the year 2020. FEC refers to the total energy used by end users, such as households, excluding the energy consumed by the energy sector itself while emissions indicate the CO2 released from the energy used. In Gällivare, the share of renewable energy in FEC is around 85 percent in 2020 [21].

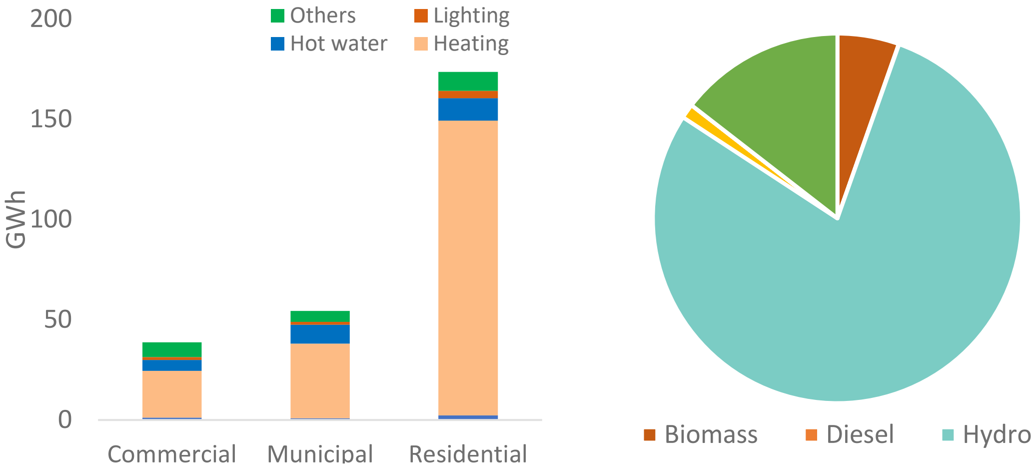

Figure 1 (left) Energy demand per sector per fuel type; (right) electricity fuel mix for Gällivare for the year 2020

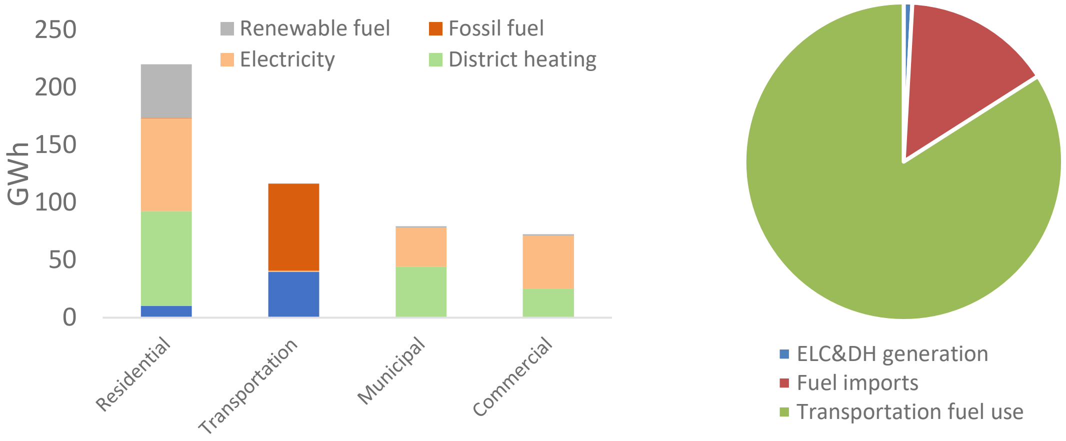

Figure 2 (left) Final energy consumption per sector per fuel type (renewable fuel includes ambient heat and biomass; fossil fuel includes, petrol, diesel and natural gas); (right) end-use CO2 emissions from fuel imports (up-stream), ELC&DH generation (tail-pipe)

Related targets

The EU has implemented varied climate and energy targets. Table 1shows the selected EU targets aimed at addressing climate change (NECPs), improving air quality (NEC), promoting renewable energy (RED), and enhancing energy efficiency. The table includes the national targets proposed by EU for its nations (common targets for all members or specific targets for Sweden) and the targets implemented by Sweden to adhere to the EU targets. It also includes local level targets proposed for Gällivare based on higher-level targets.

The targets, RED, NECP, and NEC were chosen for assessment as they are particularly relevant for the municipality and align with its targets and ambitions. Gällivare has set a municipal net-zero CO_2 emissions target for 2030 and a geographical net-zero CO_2 target for 2045. The municipality is determined to become a sustainable society with the support of the world's first fossil free sponge iron plant (Hydrogen Breakthrough Ironmaking Technology, HYBRIT, [22]), for example by utilizing industrial waste heat in the municipal district heating systems [23]. Leveraging HYBRIT and the cheap electricity in the north of Sweden, it also aims to promote and integrate hydrogen and electricity-based vehicles in the road transport [21]. Moreover, these targets directly address key aspects of sustainable development, including SDG3 (Good Health and Well-being), SDG7 (Affordable and Clean Energy), SDG13 (Climate Action), and SDG11 (Sustainable Cities and Communities). They also indirectly impact other SDGs such as SDG8 (Decent Work and Economic Growth), SDG12 (Responsible Consumption and Production), and SDG14 (Life on Land) [24] which are also the focus areas for the municipality [25].

MODELLING FRAMEWORK

The energy system of Gällivare, confined to the geographical boundaries of the municipality, is represented using an energy system optimization model. The model is developed on the TIMES modelling platform following the TIMES-City structure. TIMES (The Integrated MARKAL-EFOM System) is a bottom-up, technology-rich model generator using linear programming. It is used to represent energy systems at various scales—local, national, multi-regional, or global for analyzing energy dynamics over long time horizons [33]. TIMES-City was developed as a part of the EU SureCity project to support policymakers and city planners in developing energy strategies and enhancing climate action [34]. The model is designed to capture both energy supply and demand of system [35] as illustrated in Figure 3.

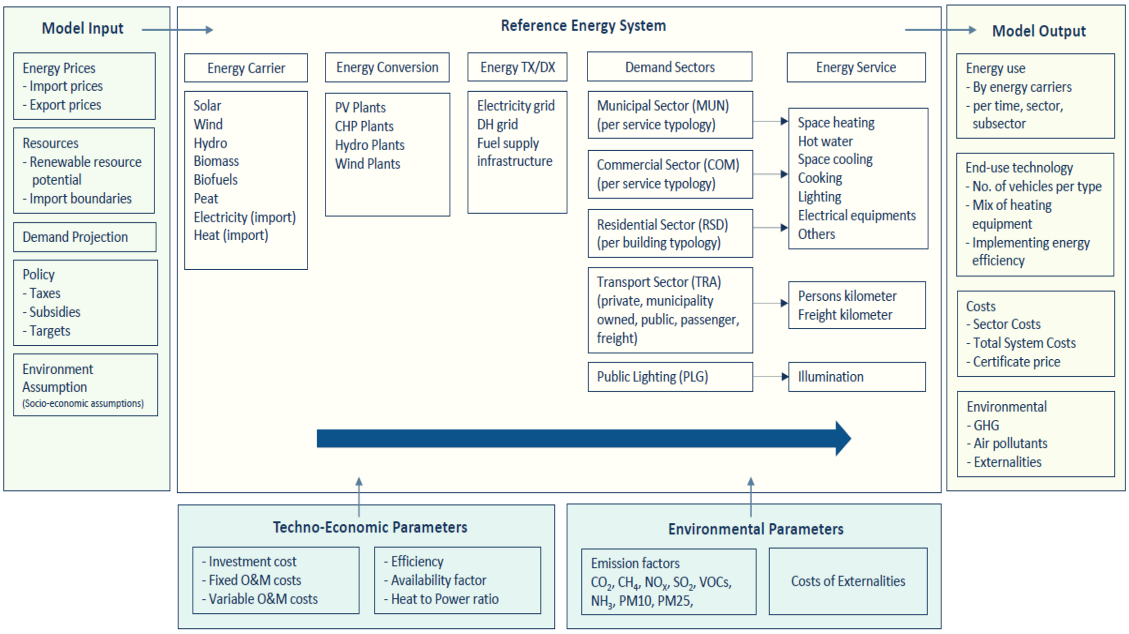

Figure 3 Conceptual description of the model

Table 1 Mapping EU targets to local level

EU targets	**National targets proposed by EU for EU nations/ Sweden**	**Swedish national targets**	**Proposed local level targets**
Renewable Energy Directive (RED): increase the share of renewable energy in the EU energy consumption to 45%, with minimum binding target of 42.5% by 2030 [26]	-Choose between 14.5% reduction in GHG emissions using renewables or at least 29% renewable share in transport sector by 2030 -0.8% annual increase in RES share in heating & cooling until 2026 & 1.1% annual increase until 2030 (binding) -49% RES share in building sector by 2030	-Generate 100% electricity from RES by 2040 [26] (included in NECP)	Include at least 29% renewable share in transport sector by 2030
National energy and climate plans (NECPs): 10-year plan outlining how EU countries intend to meet the EU energy and climate targets for 2030 [27]	Develop national long-term strategies and ensure they align with the 10-year NECPs	-Net zero GHG emissions by 2045 & subsequently negative emissions -75% emission reduction from sectors outside EU ETS by 2040 w.r.t 1990 -63% emission reduction from sectors outside EU ETS by 2030 w.r.t 1990 (attain maximum 15%, 2% & 8% respectively through accompanying measures*) -70% emission reduction in transport by 2030 w.r.t 2010 -100% fossil-free electricity by 2040 -50% more efficient energy use in 2030 w.r.t 2005 [28]	-Same as national targets† -Target for electricity production‡ and energy efficiency¤ target are excluded - Net zero GHG emissions by 2045 (Gällivare Municipality target)
National Emissions reduction Commitments (NEC) Directive: sets 2020 and 2030 emission reduction commitments for five main air pollutants [29]		Emission reduction of sulphur dioxide (SO_2) by 22%, nitrogen oxides (NO_x) by 66%, non-methane volatile organic compounds (NMVOC) by 36%, ammonia (NH_3) by 17%, particulate matter (PM2.5) by 19% by 2030 compared to 2005 [30]	Same as national targets
Energy Efficiency Directive: reduce final energy consumption by at least 11.7% by 2030 compared to 2020 EU reference scenario projection [31]	2% reduction in final energy consumption in 2030 (compared to 2020 EU reference scenario projections) [32]	-Improve energy efficiency by 50 percent compared to 2005, expressed in terms of primary energy use in relation to gross domestic product (defined in NECP)	-Energy efficiency target is excluded¤

*accompanying measures consist of carbon sequestration in forests and land, emission reductions achieved outside national borders, carbon capture and storage from biofuel combustion etc., †emissions from industry is excluded from study as it falls under EU ETS and not under the discretion of the municipality; ‡electricity generation is almost fossil free in SE1- electricity price area of Sweden, which includes Gällivare; ¤model is being developed to include the related costs of energy efficiency improvements

The supply sector includes electricity and district heating (ELC&DH) and fuel supply (SUP). ELC&DH includes all the electricity and district heating generation facilities in the municipality- hydro, solar, wind power plants and CHP plant. SUP includes all the other fuel supply including imports, extraction or cultivation of resources such as coal, biomass, diesel, gasoline, biofuels etc., The model encompasses seven demand sectors including, residential buildings (residential sector), private commercial buildings (commercial sector), municipality-managed buildings (municipal sector), transport sector, and municipality-managed public lighting (public lighting), and a simplified representation of industrial sector. Demand is seen as useful energy or as a useful energy service, e.g. persons-kilometre travelled in cars, or space heating in residential houses. Transport sector, which is discussed in detail in the study, is divided into two main categories: transport of freight and transport of individuals. It is further categorized based on whether the transport is managed by the municipality or privately. These categories are then subdivided into short-distance (intra-city) and long-distance travel (entering or exiting the municipality). Intra-city modes such as walking, cycling, and urban buses cater to short-distance transport needs, while intercity buses, rail transport, serve long-distance transport demands. Freight transport demand is met via road (heavy and light freight), rail and maritime transport.

The model optimises net system cost to meet the given demand using available resources and technologies, within the given constraints. The time frame over which the model operates spans from 2018 to 2050, with each year being divided into 12 time-slices. 2018 is the model base year but the model is calibrated for the years, 2019 and 2020. The calibration is completed using final energy consumption (or end use) data from Statistics Sweden [21], Swedish Energy Agency [36], Transport Analysis [37] and data from the municipality among others. Emission are defined either as tailpipe or upstream. Tailpipe emissions are from energy use within the municipality and are from energy conversion, distribution to end use. Upstream emissions, on the other hand, are from extracting, converting, and importing energy from outside the municipality. In this study, tailpipe emissions are applied for CO2, SO2, NOx, NMVOC, NH3, PM2.5 and PM10 while upstream emissions are only defined for CO2.

SCENARIO DEFINITION

Considering rigid municipal boundaries without accounting for the inherent variability in social, economic, and environmental aspects beyond these boundaries can lead to flawed assumptions about the future of energy system [38]. This is particularly relevant for Gällivare, as its industrialization and subsequent socio-economic changes depend on factors such as climate action and ambition at global, regional and national levels. To include this externalities, ‘glocal’ scenarios developed in the working paper (Paper III, [38]) are applied in this study. These locally relevant energy transition scenarios integrate global, regional, and national dynamics into the local context. This study employs global shared socio-economic pathways (SSPs, [39]) to incorporate global dynamics, considers regional dynamics through EU targets (as described in **Table 1**), and assumes national support for the green transition to develop 'glocal' scenarios for Gällivare. No specific local targets such as targets from local administration is considered as the chosen EU targets align with local targets and are mapped to the local level.

Since the study prioritizes examining the impact of EU targets, it focuses solely on the SSP1 pathway rather than exploring all five SSP scenarios in detail. SSP1 is chosen because certain socio-economic changes in Gällivare align with the assumptions provided in SSP1, while others do not, making it an intriguing case for the area. For example, green industrialization, including the establishment of HYBRIT and other green industries in Gällivare, is in line with SSP1. However, population growth in Gällivare, contradicts the assumptions in SSP1- where the population stabilizes. Apart from the three targets mentioned in **Table 1**, additional carbon budget (CB) scenarios are also considered. Comparing CB scenarios with other EU scenarios allows for the assessment of the effectiveness of different emission reduction strategies. It can provide insights into whether the current climate targets are sufficient or if additional measures, such as strict carbon budgets, are necessary to achieve long-term climate goals. The scenarios are described below:

Common assumptions for all scenarios

SSP1 [40] combined with national support for green industries serves as the baseline for all scenarios. In SSP1, the world progressively shifts toward a more inclusive, sustainable, and environmentally conscious development path. This scenario assumes reduced costs for renewable technologies (and hence electricity), high taxes on fossil fuels, increased growth in green industries, and improvements in the efficiency of green technologies.

National support for green industries involves fostering sustainable practices and advancing green technologies through proactive government intervention. This support manifests in several critical ways, including substantial investments in research and development and subsidies for green industries to drive innovation and growth. Renewable electricity generation is prioritized to reduce electricity costs for green industries, making sustainable practices more economically viable. Additionally, significant subsidies are provided for low-carbon vehicles to accelerate the transition to a low-carbon transportation sector. Further details on how these assumptions impact the local level are included in the working paper (Paper III, [38]). Apart from the locally defined targets described below, all other assumptions regarding fuel supply (import limits, fuel prices, taxes, subsidies), demand (demand growth), and technologies (technical specifications, cost, technology availability) remains the same in all scenarios.

Renewable Energy Directive (RED)

In the RED scenario, aligned with the EU's RED, a 29% renewable energy share in the transport sector—encompassing passenger, freight, road, and rail—must be achieved by 2030. The target is applied at the local level and extrapolated to the end of the model horizon, 2050.

Air Pollution Target (APT)

The APT scenario is inspired by the NEC to improve the local air quality. Swedish national targets set for 2020 and 2030 are mapped to the local level and are projected to 2050. The Swedish focus is on agriculture, energy consumption, energy supply, industrial processes, transport, and waste management. In this scenario, the targets are applied to the transport sector, as in Gällivare the majority of emissions are from this sector (assuming equal reduction from all identified sectors).

Carbon Target Annual (CTA)

The CTA scenario, inspired by the NECPs, includes targets for CO2 emission reduction from fuel imports, ELC&DH production, energy use in transport, residential, commercial and industrial sectors. Emissions from fuel imports include those generated during extraction or cultivation and harvesting, processing, and transportation of fossil fuels [41] and biofuels [42]. The target is to achieve net zero emissions by 2045 and is supported by interim targets for milestone years 2025, 2035, and 2040. Although the model includes emission factors for CH4 and N2O, these are excluded from the study as their sources, such as fossil fuel extraction for CH4 and agriculture for N2O [43], are not relevant for Gällivare.

Carbon Budget

The maximum aggregated anthropogenic CO2 emissions [44] to limit the global warming to 1.5°C and 2°C is determined as two different CBs for Gällivare.

Carbon Budget 2°C (CB2). The calculation of remaining carbon budget [45] for Gällivare with an 83 percent chance of not exceeding 2°C is based on the study [46], which has developed and presented the remaining CB for Sweden in accordance with the temperature and equity targets of the Paris Agreement. In the study, the regional CBs were developed in cooperation with the county administrative boards of Sweden. Our study uses this data for Gällivare located in Norrbotten county to estimate its remaining CB. The steps and assumptions involved are as follows:

1. A 14% annual reduction in CO2 emissions from 2024 to 2036 is estimated as needed to contribute to meet the Paris agreement, which is in line with the annual reduction identified for Norrbotten in [46]. This is a simplification, when the reduction in [46] encompasses all sectors, while this study excludes the industry sector, which is the most challenging to mitigate.
2. The emissions for each year, with a 14% annual reduction, is calculated using eq. 1:

$$Emissions_t = Emissions_{t-1} * \ (1 - 0.14) \tag{1}$$

3. In year 2023, the CO2 emission in Gällivare was 25 ktons ($Emissions_{2023} = 25$)
4. The carbon budget left to be used between year 2024 to 2036 is calculated using eq. 2:

$$CB_{2024\ to\ 2036} = \sum_{t=2023}^{2036} \quad Emissions_t \tag{2}$$
$$CB_{2024\ to\ 2036} = 140\ kton$$

Carbon Budget 1.5°C (CB1.5). Calculation of the carbon budget left for Gällivare with a 50 percent chance of not exceeding 1.5°C is based on the approximations in [1] and [47] which estimates that the global carbon budget left for a '50 percent chance of not exceeding 1.5°C' is 0.46 for an '83 percent chance of not exceeding 2°C'.

$$CB_{2024\ to\ 2036} = 0.46 * 140\ kton = 65\ kton \tag{3}$$

The identified CB is applied to emissions within the municipal boundary i.e., it is applied only to energy production and energy use emissions within the municipal boundary excluding export emissions. This is because the CB [46] is calculated based on the Paris Agreement following a top-down approach and excluding import emissions ensures that emissions from traded goods are not double counted by both exporting and importing countries.

RESULTS AND DISCUSSIONS

Model results are presented to evaluate whether the localized EU targets correspond or contradict each other with respect to their impact on climate and local air quality. The fuel options that are considered cost-efficient in different targets are assessed. Focusing on passenger road transport, the analysis examines the technology choices across different targets such as the changes in vehicle stock. Additionally, the sustainability status of the energy system under different scenarios is assessed using sustainability indicators.

Climate

ELC&DH accounts for the least emissions, approximately 1% in Gällivare (**Figure 4**). Despite the sector being largely decarbonized, emissions persist due to the use of peat as fuel in CHP plants. The municipality has made a conscious effort to reduce peat usage and increase biomass utilization. Currently, the CHP plants are primarily using biomass, a trend expected to continue. On average (across the scenarios and model years), around 13% of emissions stem from fuel imports (both fossil and biofuel imports). This highlights the importance of accounting for indirect emissions associated with fuel use within the municipality. The largest share, 87% on average, arises from fuel use in the transport sector.

In the RED scenario, renewable energy integration in transport cuts emissions by half by 2030, maintaining this reduction through 2050, highlighting the need for updated future targets over reliance on trends. In the CTA scenario, net zero target is attained by 2045. Import emissions decrease with the reduction in fossil fuel use and/or the adoption of biofuels characterized by very low import emissions. In the APT scenario, the air pollution targets contribute to the reduction of CO2 emissions without specific CO2 reduction targets. This shows that the localized EU air pollution targets correspond the localized EU carbon reduction targets and, in this case, resulting in 100 percent emission reduction by 2050. CB1.5 is a highly ambitious scenario which achieves net zero target before 2030, drastically reducing emissions from all sources. CB2 is a relatively less ambitious scenario achieving net zero emissions before 2040. This budget provides more flexibility to the municipality but with a trade-off concerning the temperature rise. As the CB is only applied to emissions within municipal boundary, emissions from the import of biofuels persists. Results shows that defining CBs corresponds the achievement of net zero target, however, the trajectory depends on the budget included (e.g., CB1.5 is fast track path compared to CB2).

In the following discussions, the term EV (electric vehicles) includes BEV (battery electric vehicles), PHEV (plug-in hybrid electric vehicles), and HEV (hybrid electric vehicles). Fossil fuels include diesel, gasoline, and compressed natural gas and biofuels include biodiesel, biogas, bioethanol, and biomethanol.

As mentioned, renewable energy share in the FEC is already high in Gällivare. Consequently, the EU RED is not relevant for Gällivare. The municipality should set more ambitious renewable energy targets, leveraging its advanced starting point and focusing on sectors with high improvement potential, particularly transport. For example, focussing particularly on the transport sector. With the ELC&DH sectors nearly decarbonized, the renewable energy share in final energy consumption largely depends on the transport sector. This approach will better reflect local conditions and support continued progress towards sustainable energy goals.

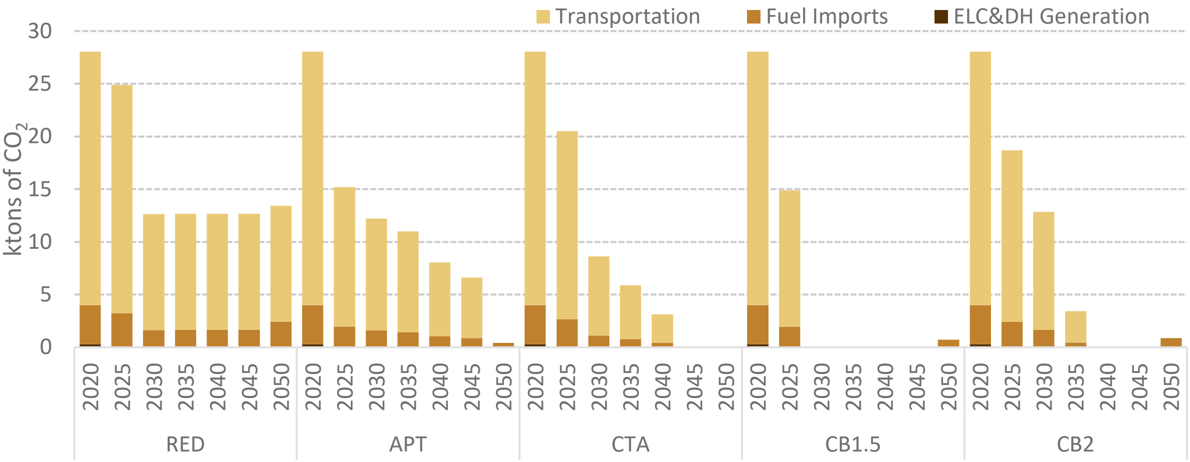

Figure 4 CO2 emissions from fuel imports (up-stream), ELC&DH generation (tail-pipe), and transportation (tail-pipe) in different scenarios

The fossil fuels used in scenarios mainly comprise of diesel for heavy freight and buses, and gasoline (major share) and natural gas for cars. In the beginning of model horizon liquid biofuels primarily comprise biodiesel (major share) and bioethanol, with biomethanol being included from 2040 for freight transport to meet climate target. Similarly gaseous biofuels, such as biogas, cars replace natural gas in cars and light freight, trains, and cars are electrified. This mix is similar in all scenarios and exceptions will be detailed.

In the RED scenario, fossil fuels are replaced by electricity in cars and light trucks, and by biofuels in buses and heavy trucks to meet renewable target (**Figure 5**). The share of electricity in fuel mix is comparatively higher around 2040. This trend is driven by the payback period of EVs, where higher initial costs are offset by lower operational costs and greater efficiency compared to ICEVs **[48]**. Currently, there is an excess of cheap renewable electricity in Northern Sweden. However, electricity demand rises across all sectors over time, including the industrial and transport sectors, leading to higher costs. This increase often triggers a shift towards biofuels as a more competitive alternative. Similar to RED, this fuel shift to biofuels is visible in all scenarios. Hence to keep the investments in EVs, it should be made affordable by investing in more cost-effective renewables.

FEC is reduced in all scenarios, primarily due to the shift to more efficient technologies for meeting travel demand. For example, among cars, BEVs are about 3 times more efficient, HEVs about 1.5 times, and PHEVs about 2 times more efficient than ICEVs **[49]**. **Figure 5** shows a major shift to EVs in passenger car transport, which is consistent across all scenarios. This indicates that all localized EU targets for carbon and air pollution reduction enhances the integration of renewable energy and improvements in energy efficiency, leading to the reduction of FEC. In the CTA, APT, CB1.5 and CB2 scenarios, the fossil-free status is achieved by 2045, 2050, 2030 and 2035 respectively. The fuel mix gradually shifts from fossil fuels to electricity and biofuels. In APT, unlike other scenarios, a significant portion of gaseous biofuels is used in cars, buses, and freight. This shift is driven by the adoption of biofuels with lower pollutant emissions to meet air pollution targets effectively.

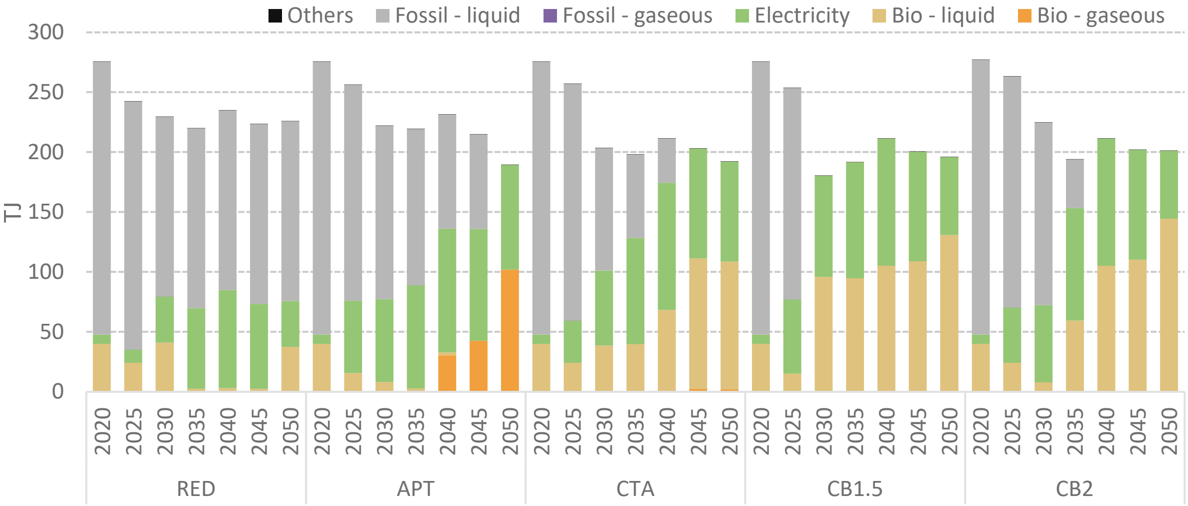

Figure 5 Fuel mix in the transport sector under different scenarios ('others' include active modes of transport such as walking and biking)

The municipality of Gällivare should set more ambitious and localized energy and emissions targets that build on transport sector. This includes continuing the transition towards EVs and promoting biofuels where appropriate. Also, planning for rising electricity demand across sectors is essential to manage costs and maintain EV competitiveness and making strategic investments in local renewable energy capacity is crucial. Additionally, the municipality should consider the implications of indirect emissions from fuel imports.

Air quality

SO2 achieves 100% reduction by 2050 in all scenarios compared to 2020 levels, primarily due to decreased reliance on fossil fuels, the major source of SO2 emissions (**Figure 6**). Despite reductions in fossil fuel usage, NOX and PM emissions persist in all scenarios (except

APT), primarily due to use of biofuels. Achieving significant reductions in these pollutants while continuing biofuel use requires further advancements in engine technologies and the adoption of next-generation biofuels [50].

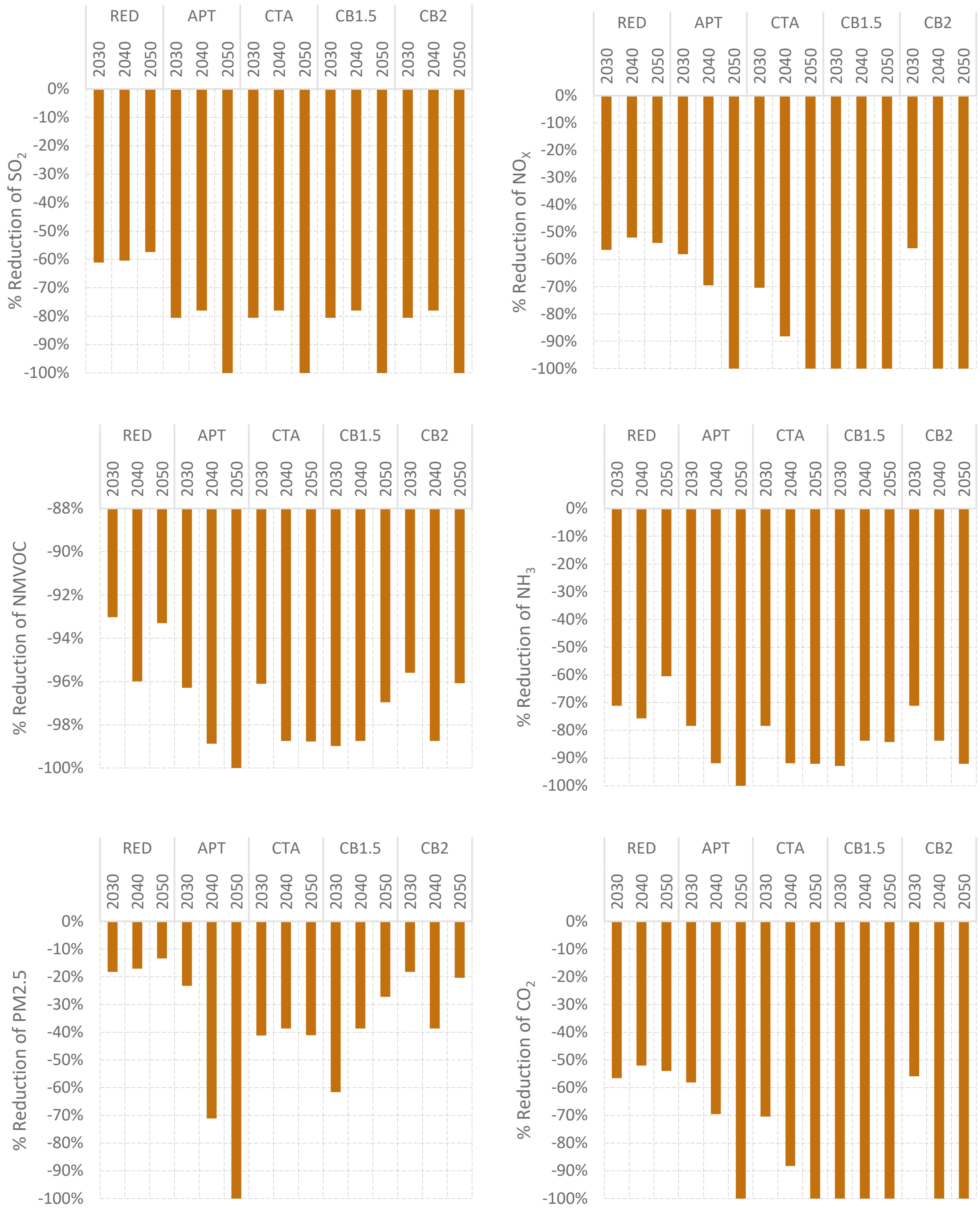

Figure 6 Air pollutant and CO2 emissions from fuel use in transport sector, represented as percentage change from the year 2020 for each scenario

The APT scenario results show that extrapolating the national air pollutant targets results in 100% reduction at local level by 2050 compared to 2020 levels. Following the APT scenario, the maximum emission reduction occurs in the CTA scenario. This is primarily due to constraints on import emissions (along with net zero target), which limit biofuel usage, encouraging a shift towards EVs, especially in passenger cars. For instance, SO2 is reduced by approximately 100%, NOX by 50%, NMVOC by around 97%, NH3 by about 80%, and PM2.5

by roughly 40% (averaged across 2030, 2040, and 2050). CTA is followed by the CB1.5 and CB2 scenarios, which achieves significant reductions due to strict carbon budget constraints that limit fossil fuel usage. REC shows the least reduction in air pollutant emissions due to the less ambitious target.

Unlike CO2 emissions, which have global implications, air pollution and air quality issues are highly local. They are influenced not only by transport but also by industrial activities and urban development. Presumably, targets for air quality improvement in Gällivare will need to be more stringent compared to 2030 reduction targets, especially considering the ongoing infrastructure developments in the area both industrial and socio-cultural. Results show that the localized EU targets for carbon reduction corresponds the reduction of air pollutants. However, the fact that a 100% reduction in air pollutants is achieved only in the APT scenario underscores the need for specific air pollution targets to effectively improve air quality.

Technology choices in scenarios (vehicle stock analysis)

Private car stock. In Gällivare, nearly 60-70 percent of emissions in the transport sector are generated by cars and buses and hence are discussed in detail in the rest of the section. In **Figure 7**, which depicts the total stock of passenger cars, there is a noticeable trend towards BEVs. Despite high initial costs, BEVs are preferred for their low operating costs resulting from cheap electricity. In the RED scenario, although over 50 percent of the vehicle stock is composed of BEVs and HEVs, PHEVs are also preferred due to the scenario's lower ambition, allowing a shift to more affordable vehicles that can run on both fossil fuels and biofuels. These hybrid vehicles offer a middle ground, with costs lower than BEVs but higher than ICEVs, and efficiency higher than ICEVs but lower than BEVs. Among the hybrid options, PHEVs are the least preferred due to their comparatively high costs when compared to HEVs though they offer higher efficiency.

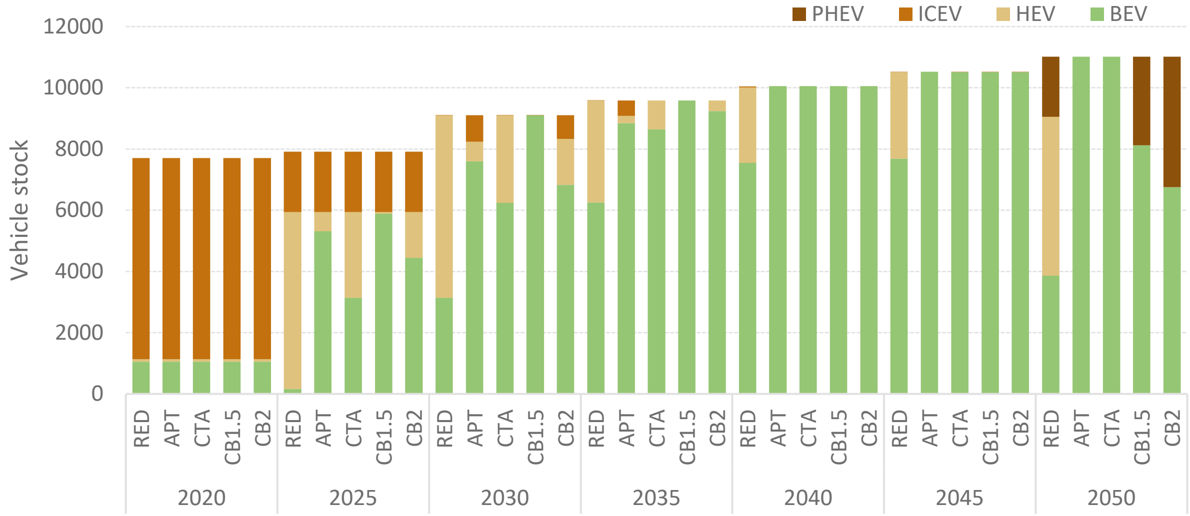

Figure 7 Total vehicle stock of passenger cars in different scenarios (BEV- battery electric vehicles, PHEV- plug-in hybrid electric vehicles, HEV- hybrid electric vehicles and ICEV- internal combustion engine vehicles)

The vehicle stock completely shifts to BEVs by 2040 in the CTA scenario, due to the strict emission targets. The restriction on import emissions also plays a significant role here, limiting the import of biofuels and thereby driving the shift to BEVs. This shift is further supported by the applicability of low-emission fuels to other subsectors such as buses or freight transport, as passenger cars are comparatively easier to electrify. Similarly, in the APT scenario, air pollution targets restrict the use of biofuels due to their associated pollutants, which drives the switch to BEVs. However, a few investments in ICEVs are still made, resulting in around 5-10% of the vehicle stock continuing to use fossil fuels. In these cases, ICEVs are preferred over

HEVs or PHEVs due to cost considerations, as the air pollutant targets allow some flexibility for fossil fuel usage. Also, the fossil fuels are blended with biofuels. In the CB1.5 scenario, PHEVs are preferred around 2050 over HEVs due to their higher compatibility with biofuel blends, which is comparatively lower for HEV technology. However, in the CB2 scenario, ICEVs, HEVs, and PHEVs are all preferred, utilizing the flexibility allowed in the CB scenario.

Bus stock. ICEVs are highly invested in the bus vehicle stock, as shown in **Figure 8**. However, to meet the respective scenario targets, BEVs are also invested in, followed by the usage of biofuels in ICEVs. BEVs receive less investment due to their higher costs compared to ICEVs. In the case of buses, BEVs are twice as expensive, and PHEVs and HEVs are 3-4 times more expensive than ICEVs on average (across different models) **[49]** . The RED scenario shows the least investment in BEVs due to cost and target considerations, when compared to other scenarios with more ambitious targets. The APT scenario shows the highest investment in BEVs due to stricter air pollutant targets. The CTA, CB1.5, and CB2 scenarios show similar investments in BEVs. In the CTA scenario, this is due to restrictions on import emissions. In the CB1.5 and CB2 scenarios, it is due to the strict carbon budgets (CB) that must be achieved, so early investments in BEVs support this goal. These scenarios also show investments in ICEVs that use only biofuels (with the CTA scenario additionally shifting to fuels with the lowest CO_2 emissions).

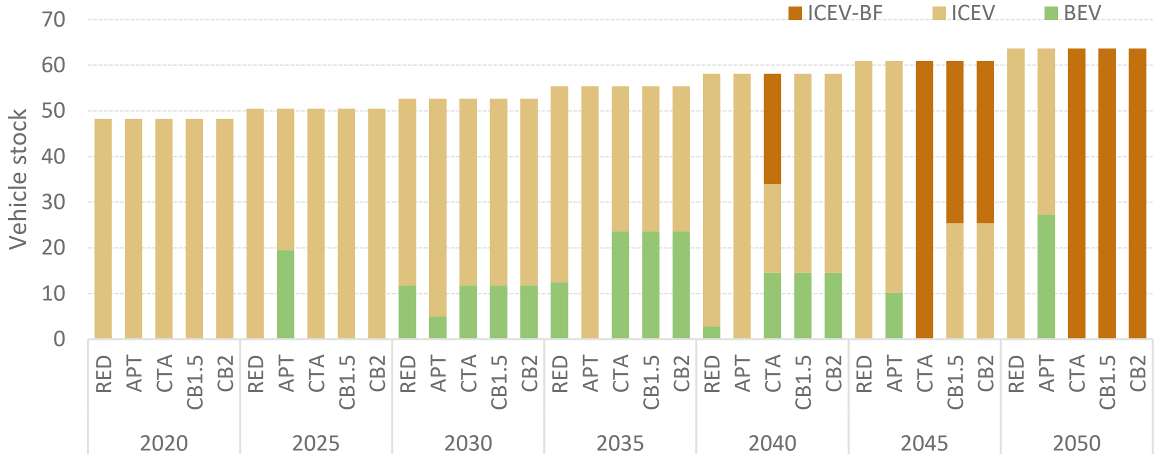

Figure 8 Total vehicle stock for inter and intra city buses (BEV- battery electric vehicles, ICEV- internal combustion engine vehicles, ICEV-BF – ICEV only using biofuels)

The above results show that the investments are highly reflective of the targets and impacts vehicle investments differently. This emphasizes the necessity for local-level targets to be designed with a comprehensive understanding of the system, rather than following higher-level targets. For example, no investments have been made in hydrogen fuel cell vehicles (HFCVs), and there are no specific policies supporting hydrogen adoption. However, HYBRIT can be seen as a potential hydrogen supplier and the municipality can design infrastructure and policies based on this potential starting with the municipality’s vehicle fleet.

Sustainability result indicators

A set of sustainability indicators, as proposed in **[18]**, is applied to evaluate the sustainability status of each energy transition pathway (here named as scenario). These indicators (**Table 2**) are either included in the model or are assessed outside the model.

The indicator selection process was designed to ensure a comprehensive assessment of sustainability within the energy transition pathways for northern Swedish municipalities. The selection process was conducted in three phases: identifying globally recognized SDGs and their relevance to Sweden, refining the indicators to those pertinent to the energy transition in Sweden’s northern municipalities, and further filtering them for integration into the energy system optimization model (ESOM). The study considered both quantitative and qualitative criteria to ensure that the selected indicators were not only measurable but also reflective of local sustainability challenges. Quantitative criteria included data availability, measurability, and alignment with model parameters, ensuring that the indicators could be effectively incorporated into the ESOM for scenario analysis. Meanwhile, qualitative criteria focused on policy relevance, local applicability, and stakeholder priorities, ensuring that the selected indicators resonated with municipal sustainability goals.

Table 2 Applied sustainability indicators

SDG	SDG Target	Applied sustainability indicator
SDG7	T7.1.1	Marginal cost of electricity and district heating
	T7.2.1	Renewable energy share in total final energy consumption
	T7.3.1	Distance to EU target for primary & final energy consumption
SDG8	T8.4	Material footprint associated with energy transition
SDG11	T11.1	Marginal cost of space heating, electricity and district heating Marginal cost of travel
	T11.6.2	Annual mean levels of fine particulate matter (e.g. PM2.5 & PM10)
SDG12	T12.2	Material footprint associated with energy transition
SDG13	T13.2	Annual GHG emissions in total and per sector

To justify the selection of thresholds, the study employed a combination of national and international benchmarks, local policy targets, and expert consultations. For instance, SDG indicators that aligned with existing national climate and energy policies, such as Sweden’s net-zero emissions goal for 2045, were prioritized. Additionally, thresholds for renewable energy share and energy efficiency improvements were set based on Swedish and EU energy policies. In cases where standard thresholds were unavailable, the study established new benchmarks through municipality-level discussions and contextual analysis. Some indicators, such as the material footprint of electric vehicle adoption, required a hybrid approach, where model outputs were supplemented with external estimates to quantify sustainability trade-offs. This rigorous and structured methodology ensured that the indicator selection process was both data-driven and policy-aligned, enabling a holistic assessment of sustainability across different energy transition pathways (Refer [18] for further details).

Heatmap is employed to illustrate the results of the application of the sustainability indicators (**Figure 9**). The result may not represent all the changes throughout the model horizon but reflects the status in the year 2050. The quantitative values of the result indicators for T7.3.1 and T8.4 are calculated outside the model based on the model results, while all other indicators are directly obtained from the model results. For T7.1.1, fossil fuel share in FEC is included rather than renewable share to have a common base for comparison.

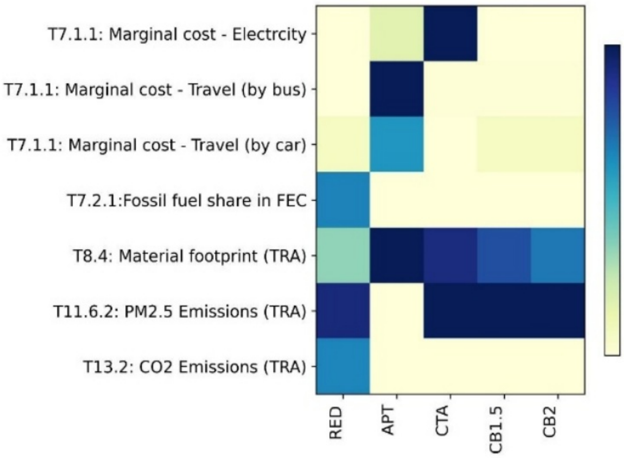

Figure 9 Sustainability indicator values for the year 2050 for Gällivare energy system (TRA -transport sector). Higher indicator values (shown in blue) indicate negative impacts on the environment or society, while lower values (shown in yellow) indicate positive impacts

The heatmap can be divided into two halves, with the upper half representing economic sustainability [51] linked to economic impacts, and the lower half focusing on environmental sustainability [51] related to environmental degradation. The economic sustainability is indicated using the marginal cost of services such as electricity, travel by car and bus. Marginal cost of service refers to the additional cost incurred to meet one more unit of energy demand (or energy service), in this context its one unit of electricity supply or one unit of passenger-km travel. Marginal cost of electricity is high in scenarios with high BEV penetration (CTA, APT) due to the increased demand and resulting competition for the supply. The variation in marginal cost of travel by bus and car in the different scenarios aligns with the outcomes of fuel use (**Figure 5**) and vehicle stock (**Figure 7**, **Figure 8**). In bus travel, the cost initially increases with the adoption of BEVs and use of biofuels, but the long-term benefits from BEVs (particularly low running cost), eventually leads to cost reduction. In cars, due to the ease of electrification compared to other vehicles, such as buses, all scenarios show significant investment in EVs, which initially increases costs which decreases subsequently. The APT scenario differs from the other scenarios in both bus and car cases, due to constraint on biofuel use, resulting in increased investments in BEVs and the selection of least air pollutant-emitting biofuels. This shift leads to increased costs throughout the model horizon.

Hence, in terms of economic sustainability, the RED, CB1.5, and CB2 emerge as more sustainable scenarios, indicating a lower transition costs thus minimizing economic burden. Conversely, the CTA and APT scenarios involve higher costs for transition, placing a comparatively higher greater burden on society. In the environmental sustainability assessment, the APT scenario ranks as the most sustainable, followed by CB2, CB1.5 and CTA. While these scenarios (CBs and CTA) reduce CO_2 emissions by 2050, they have higher air pollutant levels indicating its impact local air quality and health. The RED scenario is the least sustainable due to high environmental impacts, highlighting the need for greater ambition.

The primary differences across these scenarios lie in the specific targets they aim to achieve and the pace at which these targets are pursued. The variations reflect differing priorities in what is considered most critical—whether it be reducing greenhouse gas emissions, minimizing air pollution, or adhering to carbon budgets—and the speed at which these goals are met, ranging from gradual transitions as in CTA to more immediate, aggressive measures as in CB1.5. One would assume that the implementation of stringent policies would result in high social burden, but the results indicate otherwise.

CONCLUSION

This assessment of the impact of implementing EU targets at the local level from a sustainability perspective showed that the localized EU targets correspond each other. None of the EU targets- Renewable Energy Directive, National Energy and Climate Plans (climate) and National Emissions Reduction Commitments Directive (air quality) - contradict each other when localised. Localized climate and air quality targets effectively support the integration of renewable energy, improvements in energy efficiency, and reductions in final energy consumption. Localized air quality targets correspond carbon reduction targets, and net zero is achieved. While inclusion of carbon budget supports the achievement of net-zero targets, the trajectory depends on the level of ambition, including the carbon budget and the timeframe set for achieving those limits. While localized EU targets for carbon reduction corresponds air pollutant reductions, a 100% reduction in air pollutants is achieved only in scenario with specific air pollution targets.

While the targets enhance environmental sustainability, the various technology and fuel choices made to achieve local-level targets initially increase service costs potentially impacting the economic sustainability, highlighting both the benefits and drawbacks of these options. However, over the long term, these costs decrease (based on the technology chosen e.g. the low operational costs of EVs reduce travel expenses). However, a comprehensive policy approach is essential to effectively address these challenges and minimize societal burdens. This could include subsidies for EVs, incentives for biofuel adoption, support for public transportation initiatives.

The results align with similar studies assessing the benefits of carbon reduction policies on air pollution at both national [14] and local levels [15]. The latter study identified increased air pollutant emissions in scenarios utilizing biofuels and suggests the use of electric vehicles and hydrogen fuel cell vehicles. However, due to the high costs, hydrogen fuel cell vehicles were not invested in. Future work could expand the industrial sector in the model to include HYBRIT and evaluate its potential in integrating hydrogen fuel cell vehicles into the transport sector. This is particularly relevant given the growth of hydrogen industries in Gällivare and northern Sweden, where municipal plans are also aligned with the integration of hydrogen-based vehicles.

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