Marginal and Fuel mix Approaches in Urban Climate Planning: Insights from Bodø and Ålidhem

HYBES

Interreg
Northern Periphery and Arctic
Co-funded by the European Union

Itai Danielski, Moa Mattsson, Truong Nguyen, Gireesh Nair
Department of Applied Physics and Electronics, Umeå University, Umeå, Sweden

Content

1 Introduction

Climate change presents an urgent global challenge, necessitating immediate and sustained efforts to reduce greenhouse gas (GHG) emissions. In response, the European Union (EU) has committed to reducing net GHG emissions by at least 55% by 2030 compared to 1990 levels, with the overarching goal of achieving climate neutrality by 2050 [1]. The EU's mission to establish 100 climate-neutral and smart cities by 2030 has catalyzed widespread interest, with 377 cities applying to participate, reflecting a growing commitment to urban-scale climate action. Member states have adopted varying targets aligned with this ambition—for example, Sweden aims for climate neutrality by 2045, targeting an 85% reduction in emissions, with the remainder offset through natural and technological sinks [2].

This study assesses the energy and emissions profiles of Bodø (Norway) and Ålidhem (Sweden), offering insights into the effectiveness of local climate strategies and the importance of system-level thinking in achieving carbon-neutral urban development.

2. Methodology

This study investigates energy resources and demand within two spatial contexts: the city of Bodø in Norway and the Ålidhem district in Umeå, Sweden. The research employs a two-step methodological framework. Initially, Baseline Scenario is developed using statistical data to estimate annual final energy demand, resource consumption, and direct emissions for each case study area. Subsequently, a series of future scenarios are constructed to assess the potential of various climate mitigation strategies aimed at achieving net-zero emissions by 2040.

The analytical approach integrates energy consumption from both building and transportation sectors, utilizing a Life Cycle Assessment (LCA) framework to evaluate environmental impacts across different energy supply strategies. Two LCA perspectives are applied: the fuel mix approach, which reflects average grid conditions, and the marginal approach, which considers the impact of incremental energy demand on the most likely marginal energy source. A series of future scenarios are developed to explore potential pathways toward achieving net-zero emissions. The scenarios incorporate measures such as building retrofits, increased adoption of electric vehicles and electric public transport, and the installation of rooftop photovoltaic systems. The outputs are evaluated in terms of energy resources and emissions, providing insights to inform sustainable urban planning and decision-making.

2.1 Case Study

2.1.1 Bodø city, Norway

Bodø is a coastal city located just north of the Arctic Circle and serves as the administrative center of Nordland County (see Figure 1). As of 2025, the municipality has a population of approximately 53,700 and has experienced steady demographic growth over the past decade, characterized by a relatively young population profile. In recognition of its cultural significance, Bodø has been designated the European Capital of Culture for 2024. It is currently undergoing major urban transformation, including the relocation of its airport, which is scheduled to be completed by 2030. Nearly all of Bodø's electricity supply is derived from hydropower, reflecting Norway's strong renewable energy base. In addition, the city has articulated ambitious plans to develop green hydrogen production as part of its broader sustainability and energy transition strategy.

Figure 1. Bird view of the Bodø city marked with a red and its location in Norway. Source Google earth.

2.1.2. Ålidhem, Umeå, Sweden

Ålidhem is a residential district situated approximately three km southeast of central Umeå, Sweden, with a population of around 9,000 residents [3]. Developed between 1966 and 1973 as part of Sweden's Million Programme, the area is characterized by a high concentration of apartment buildings, many of which serve as student housing due to its proximity to Umeå University and Norrland's University Hospital. The district comprises 161 residential buildings over a land area of 0.95 km² (see Figure 2), with building heights ranging from two to six floors and a total heated floor area of 425,503 m².

Space heating and domestic hot water (DHW) are provided through the local district heating network, with no cooling systems installed. Ålidhem hosts a diverse population, including students, families, and elderly residents. Ålidhem Centrum functions as a commercial and social hub, offering retail services, cultural venues, and community facilities.

The district has undergone substantial energy-efficiency upgrades under the "Hållbara Ålidhem" initiative, which aimed to reduce energy consumption by 50% [4]. Key measures included the installation of 2,650 m² of solar panels, modernization of ventilation and heating systems, and integration of washing machines into the district heating network. Transportation infrastructure in Ålidhem is well-developed, featuring frequent bus services to the city centre and other parts of Umeå [5], as well as enhanced cycling routes connecting the district to Umeå University and the eastern train station.

Figure 2. Bird view of the Ålidhem district marked with a red circle and its location in Sweden (small map in left bottom corner). Source Google earth.

2.2. Modelling tools

The study used the following simulation tools.

2.2.1. City Energy Analyst (CEA)

CEA is an urban building energy modelling tool designed to support the planning of sustainable and energy-efficient cities. Developed at ETH Zurich, it enables detailed simulations of energy demand, supply, and infrastructure across buildings and districts. CEA integrates data on building geometry, usage patterns, and climate to evaluate scenarios such as retrofitting, renewable energy integration, and district heating systems. It supports decision-making by visualizing energy flows and identifying optimal strategies for reducing emissions and improving efficiency, and is accessible via a desktop interface, command line, or parametric design platforms like Rhino/Grasshopper [6].

2.2.2. Low Emissions Analysis Platform (LEAP)

LEAP is a flexible, scenario-based modelling tool developed by the Stockholm Environment Institute for energy policy analysis and climate change mitigation planning. It enables to simulate energy demand, supply, emissions, and resource use across sectors and scales—from cities to entire countries. LEAP supports a wide range of methodologies, including bottom-up and top-down modelling, and allows for integrated assessments of greenhouse gases, local air pollutants, and social cost-benefit analyses. Its intuitive interface and low initial data requirements make it accessible to both experts and newcomers, while its powerful scenario manager helps evaluate the impacts of individual policies and combined strategies over medium- to long-term horizons [7].

2.2.3. Polysun SPT

Polysun SPT is a simulation tool tailored for photovoltaic (PV) system planning and optimization. It enables users to model entire solar installations with high precision, incorporating elements such as roof geometry, shading, inverter configurations, battery storage, electric vehicles, and heat pumps. With features like automatic 3D building visualization, CAD export, and integration of real-world weather data. Polysun SPT supports detailed yield forecasts, financial analyses, rapid system comparisons, and self-consumption calculations [8].

2.3 Baseline Scenario

The baseline scenario represents the current energy and emissions for one year and is based on statistical data from different sources. For Ålidhem the baseline scenario represents the year 2023, and 2024 for Bodø. The following section provides details on the data used in the model.

2.3.1. Final energy demand in buildings

(I) Bodø

The final demand in the building stock in Bodø was modelled using data on buildings and heating systems. Table 1 lists the type of buildings, floor area, and average specific energy used to construct the Bodø model. Data was received from the Bodø municipality [9].

Table 1. The type of buildings that were use in the model

Building type	Number of units	Floor area	Average energy demand
Apartment	7,501	857,389 m^2	100 kWh/m^2
High rise	7,876	1,070,827 m^2	180 kWh/m^2
Row House	4,667	603,792 m^2	140 kWh/m^2
Single-family house	6,289	1,343,254 m^2	180 kWh/m^2
Commercial	1,109	746,494 m^2	250 kWh/m^2
Total	**27,442**	**4,621,756**	

A representative model of the use of heating technologies in the building sector in Bodø was created based on the data from the municipality and Norway's national databases [10] on energy use in buildings (Table 2). The model assumes that district heating is connected only to commercial buildings, and stoves are used only in raw and detached houses.

Table 2. Share of type of heating technology by type of building.

Building type	Heat pump	Direct resistance heating	Wood stove	District heating	Total
Apartment	44.4%	55.6%	0	0	100%
High rise	44.4%	55.6%	0	0	100%
Row House	38.3%	48%	13.7%	0	100%
Single-family	38.3%	48%	13.7%	0	100%
Commercial	36.8%	46%	0	17.2%	100%

(II) Ålidhem District

A CEA model of 21 multi-story residential building in the Ålidhem district was developed to calculate the final energy demand. The model was then calibrated and validated with measured data from these buildings. After validation the model was extended to include all district residential buildings. Building construction properties were obtained from the blueprints of the buildings. Data for electricity- and domestic hot water use was obtained from [11] and [12]. Occupancy data, indoor temperature, and seasonal change in electricity use and domestic hot water hot use were modelled according to the Swedish guidelines for energy in buildings (SVEBY) [13], see also values in Table 3.

Table 3. Selected values used for the Ålidhem model [13]

Modelled parameter	Value used
Occupancy	14 hours per day
occupancy density	30 m^2/person
Body heat	80 W/person
indoor temperature	21°C

2.3.2. Energy use in transport sector

(I) Bodø

The modelling of private transportation in Bodø was conducted using locally specific statistical data [14]. The distribution of vehicles by fuel type is presented in Table 4, providing a detailed overview of the current vehicle fleet composition. For the purposes of this analysis, an annual average travel distance of 9,073 km per personal vehicle was assumed, based on estimation from the municipality.

Table 4. Number of vehicles by fuel type.

Type of car by fuel	Number of cars
EL	5971
Bensin	7051
Diesel	10478
Hybrid	2772
Total	26272

(II) Ålidhem District

The transportation model for Ålidhem was developed using comprehensive local data on key parameters, including population size, vehicle fleet composition (e.g., passenger cars, buses, and trucks), and fuel consumption rates across different vehicle categories. Additional data was collected on travel distances, trip frequencies, and trip purposes (e.g., commuting, freight transport). A summary of the collected data is presented in Table 5, which forms the basis for estimating energy use and emissions associated with transportation activities within the district.

Table 5. Mobility statistic related to Umeå city and Ålidhem specifically.

Modelled parameter	**Value used**	References
Total population	6911 persons	[15]
Population in driving age	4115 persons	[16]
Number of households	4136 households	[17]
Average distance per travel	12 km per travel and person	[18]
Average travel per day	4 travels per person and day	[17]
Travel shares by travel mode	Walking 49.7%, cycling 30%, private cars 18%, electric bicycle, 2%, bus 0.3%	[18]
Car accessibility	0.243 cars per households	[17]
Share of car stock by fuel	Gasoline 44%, Diesel 37%, EV 17%, Ethanol 2%	
Total city bus travel	4,029,231 km per year	[18]
Bus travel allocated to Ålidhem by population	7.84% of Umeå city population[2]	[15]
Share of bus stock by fuel	Diesel 64%, electric bus 36%	[17]

2.3.3. Solar PV production

The simulation of solar photovoltaic (PV) potential in Ålidhem was conducted using Polysun SPT, with input parameters including roof area, orientation, and surface interference. The model employed monocrystalline PV modules measuring 2278 mm × 1134 mm, each with a nominal power output of 565 W and a standard test condition (STC) efficiency of 21.9%. The simulation assessed the district's potential solar energy production across various roof orientations, as well as the aggregate production capacity.

A total of 91 buildings were included in the analysis, comprising 29 buildings with hip roofs (14° slope) and 62 buildings with flat roofs. For hip-roofed buildings, only the long south-facing roof sections were considered, with PV panels installed on the roof wherein the tilt angle is the same as the slope of the roof. Roofs with limited surface area in the south-facing direction were excluded due to insufficient installation potential. Only buildings with a south-north orientation of the long façade were modelled for PV deployment. In contrast, flat-roofed buildings were modelled in their entirety, regardless of orientation, with PV panels installed at a 45° tilt angle.

The simulation assumed no integration of electrical storage systems, thereby constraining the maximum electricity production from PV systems to not exceed the minimum electricity demand of the buildings. This condition is typically met during the summer months, when solar irradiance is highest and electricity demand is lowest, ensuring that the generated electricity can be fully utilized without the need for storage.

Table 6. Selected values used for the solar PVs production model. Source: Database Polysun SPT.

Modelled parameter	Value used
PV model	Monocrystalline panels
PV size	2278 mm X 1134 mm
nominal power	565 W
efficiency	21.9% STC tested

2.3.4. Energy production and supply

The model of the energy systems considered in the study includes the entire energy production chain, from natural resources to energy services. It considers the conversion efficiencies of the different energy production technologies for heat and power, as listed in Table 7.

Table 7. Performance parameters of energy supply technologies. Values are based on a LHV of fuels. Negative value of efficiency indicates that electricity is used for the operation of the boilers [19].

Technology	**Conversion efficiency (%)**	
	Heat	**Electricity**
District heat production		
Coal boiler [a]	89.0	-2.0
Fuel oil boiler [b]	90.0	-1.0
Natural gas boiler [c]	103.0	-0.15
Wood chips boiler – small-scale [d]	89.0	-2.0
Wood chips boiler – with FGC [e]	114.0	-2.5
CHP steam turbine, wood chips [d]	76.2	28.2
CHP steam turbine, MSW chips [d]		
Standalone power production		
Biomass steam turbine [f]	-	45.0
Coal-based steam turbine [f]	-	46.0
Natural gas combined cycle [f]	-	56.0

[a] Similar electricity use to woodchip boilers, based on: E. Ahlgren, E. Andersson, E. Axelsson, M. Börjesson, E. Fahlen, S. Harvey, et al., Biokombi Rya – Final Report from Sub-projects (In Swedish: Biokombi Rya –Slutrapporter Fr°an Ing°aende Delprojekt), in CEC report 2007:3, Centre for Coordinated Energy Research (Chalmers EnergiCentrum-CEC), Chalmers University of Technology, Göteborg, Sweden, 2007, web-accessed at http://publications.lib.chalmers.se/records/fulltext/65604.pdf

[b] Assumed electricity use of 1%

[c] Small–scale boilers

[d] Without flue gas condensation; auxiliary electricity consumption of 2.2% of the heat generated

[e] Without flue gas condensation

[f] Based on: Danish Energy Agency, Technology Data for Energy Plants – Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion, Danish Energy Agency, 2012. Web-accessed at http:// www.energinet.dk/SiteCollectionDocuments/ Danskedokumenter/Forskning/Technology_data_for_energy_plants.pdf.

The model also considers the fuel cycle of fuels, i.e., the losses during fuel production as percentage of the fuels' energy content. Calculation of GHG emissions is based on the emission factors of the different fuels from Energyforetagen [20], as listed in Table 8. A value of 18 kg/MWH was used as the Norwegian national emission factor for electricity production.

Table 8. Fuel cycle energy and emission factors of fuels [20].

Fuel type	Emission factor (kgCO2/MWh)		Fuel cycle energy
	Sweden	Norway	(%)
Coal	384	384	10
Oil	297	297	11
Natural gas	245	242	9
LPG		271	9
Pellets	18	13	11
Forest biomass	7	7	4
Municipal solid waste	147.5		-
Wood fibre		3	4

In Ålidhem, the entire heating demand is met through the municipal district heating (DH) network, whereas in Bodø, only a limited number of buildings are connected to the DH system. In Bodø, approximately 44.9 GWh of bioenergy is consumed annually in private households, primarily using wood stoves and wood boilers. Majority of buildings rely on electricity as their primary heating source, delivered via heat pumps or direct electric heating systems.

The technological configurations of the DH systems in Ålidhem and Bodø differ, as detailed in Table 9. Both systems are predominantly biomass-based, but the DH system in Ålidhem incorporates combined heat and power (CHP) generation, contributing electricity to the local grid in addition to heat. In Bodø, an electric boiler is utilized during periods of electricity overproduction, whereas in Ålidhem, it serves as a peak-load production unit. In both locations, fossil-based heat production is employed to meet peak demand, highlighting the need for further decarbonization of backup heating sources.

Table 9. The share of heat production technologies in the DH plants in Ålidhem and Bodø.

	Technology	**Share of total yearly production in 2023**
Ålidhem [21]	- CHP biomass	18.7%
	- CHP waste	38.0%
	- Direct condenser	12.1%
	- Heat pump	6.5%
	- Biomass boiler	11.6%
	- Pellets boiler	1.5%
	- Electric boiler	0.9%
	- Biofuel boiler	0.5%
	- Fossil oil boiler	0.2%
Bodø [22]	- Pellets boiler	81.9%
	- Flex electricity	16.8%
	- LPG boiler	1.3%

The electricity systems in Sweden and Norway are distinguished by a high share of low-carbon and renewable energy sources, as detailed in Table 10. Hydropower serves as the backbone of both systems, offering substantial flexibility and functioning as a key balancing resource. Nuclear power, primarily in Sweden, contributes a stable baseload supply, ensuring reliability in energy delivery.

Over the past decade, wind power has experienced significant growth and now constitutes a notable portion of the fuel mix in both countries. In contrast, fossil fuels play a minor role in electricity generation, resulting in comparatively low carbon emissions relative to many other national energy systems. This composition positions Sweden and Norway among the leading countries in terms of clean electricity production and supports their broader climate and energy transition goals.

Table 10. The national share of power production technologies in Sweden and Norway.

	Technology	Share of total yearly production in 2023
Sweden [23]	Hydropower	39.9%
	Nuclear power	29.2%
	Wind power	20.6%
	Thermal power	7.8%
	Solar power	1.9%
	Fossil based	0.6%
Norway [24]	Hydropower	89.8%
	Wind power	9.3%
	Thermal power	0.9%

2.4. Future Scenarios

There are many possible ways in which urban areas could be developed in the future. Some changes could occur spontaneously due to current energy prices, cultural aspects, and current policies, and some will need intervention. The model in this study investigate by looking how possible changes in transport, population, building construction, production technology, and policy interventions will affect emissions reduction to year 2040.

2.4.1. Bodø

(i) Business as usual (BAU)

This scenario assumes that there will be no changes in current policies instruments in the future and therefore, historical trends will continue. By 2050 it is expected that the population will increase by 18%. The growth in the car fleet in Bodø considered to follow the population growth with increase share of electric cars following historical trend since year 2000. According to these trends petrol vehicles will phase out in 2034, diesel vehicles will phase out in 2042, and electric vehicles (EVs) will dominate the car stock with 100% by 2050.

There is no change to the public bus fleet and the energy production in Norway considered to remain as its current fuel mix, which is dominated by hydro power.

(ii) Changes to heating systems in the buildings

Several future scenarios were developed to evaluate potential transitions in heating systems across various building typologies. The scenarios focus on the replacement of existing technologies with alternative heating solutions. The scenarios considered are District Heating (DH) replaces (i) Resistance Heaters (RH), (ii) Heat Pumps (HP), in apartment buildings, high-rise buildings and commercial buildings. Further an additional scenario was developed wherein HP replaces RH across all building types.

These scenarios aim to assess the implications of different heating system configurations on energy use and greenhouse gas emissions, considering building-specific characteristics and technology performance.

(iii) Transport scenario

In addition to the change to private electric vehicles in the BAU scenario, a transport scenario for the public bus fleet was included. Currently, 1,945,000 km of buss travel is done by electric buses and 605,767 km of buss travel is done by diesel. Under this scenario all buses will be electric by 2025.

2.4.2. Ålidhem

(i) Business as usual (BAU)

This scenario assumes that historical trends will continue to the year 2040 and therefore no new policy instruments will be applied. No population growth in Ålidhem as there is no plan for further development in the district.

In addition, this scenario considers standard practice of building maintenance, which includes replacement of windows, roof tiles and roof insulation, electric appliances, and water tabs. Such building renovations are recommended after 50 years of building use. Electric appliances are replaced more often. The effect on energy demand of these building retrofitting measures was studies extensively by 20 of the district buildings in the Ålidhem district [25].

(ii) Transport Scenario

This scenario assumes that the share of private EVs in the district is similar to the national trend in the private market, which is yearly on average 1.8% of the total vehicle stock [26].

(iii) Intensive renovation scenario

This scenario builds upon the Business-As-Usual (BAU) retrofitting measures by incorporating additional insulation of building façades. The renovation strategy reflects practices implemented in a pilot project within the Ålidhem district, which involved comprehensive upgrades to one building over recent years [25]. In addition to standard maintenance activities—such as window replacement, roof insulation, and upgrades to electrical and plumbing fixtures—this scenario emphasizes thermal envelope improvements to enhance energy efficiency and reduce heating demand.

(iv) PV Scenario
This scenario explores the increased deployment of rooftop photovoltaic (PV) systems across the Ålidhem district. It assumes that all electricity generated by the PV installations is consumed locally, thereby avoiding overproduction and the need for grid export. To maintain cost-effectiveness, the scenario excludes the integration of electricity storage systems, which are considered economically unfeasible under current conditions.

As a result, the maximum simulated electricity output from PV systems is constrained to remain below the district's minimum electricity demand at all times. This design approach ensures optimal utilization of solar energy while avoiding surplus generation, particularly during periods of low demand and high solar irradiance, such as the summer months.

3. RESULTS

3.1. Bodø city

3.1.1. Current state in 2024

Figure 3 illustrates a Sankey diagram tracing the conversion of primary energy resources into final energy services within the building sector and private transportation in Bodø. The analysis focuses exclusively on heat and electricity consumption in buildings and energy use in private vehicles.

The total annual energy input amounts to approximately 945 GWh, sourced from a mix of energy carriers. Hydropower dominates the supply, accounting for 67% of the total, followed by biomass and woody products (10%), fossil fuels (13%), and wind power (7%). Both electricity generation and district heating systems primarily utilize renewable energy sources, whereas fossil fuels are predominantly consumed in the transport sector.

Of the total energy resources, approximately 78% are converted into useful energy for building operations, while 12% are allocated to transport. The remaining 9% represents conversion and transmission losses occurring during energy transformation.

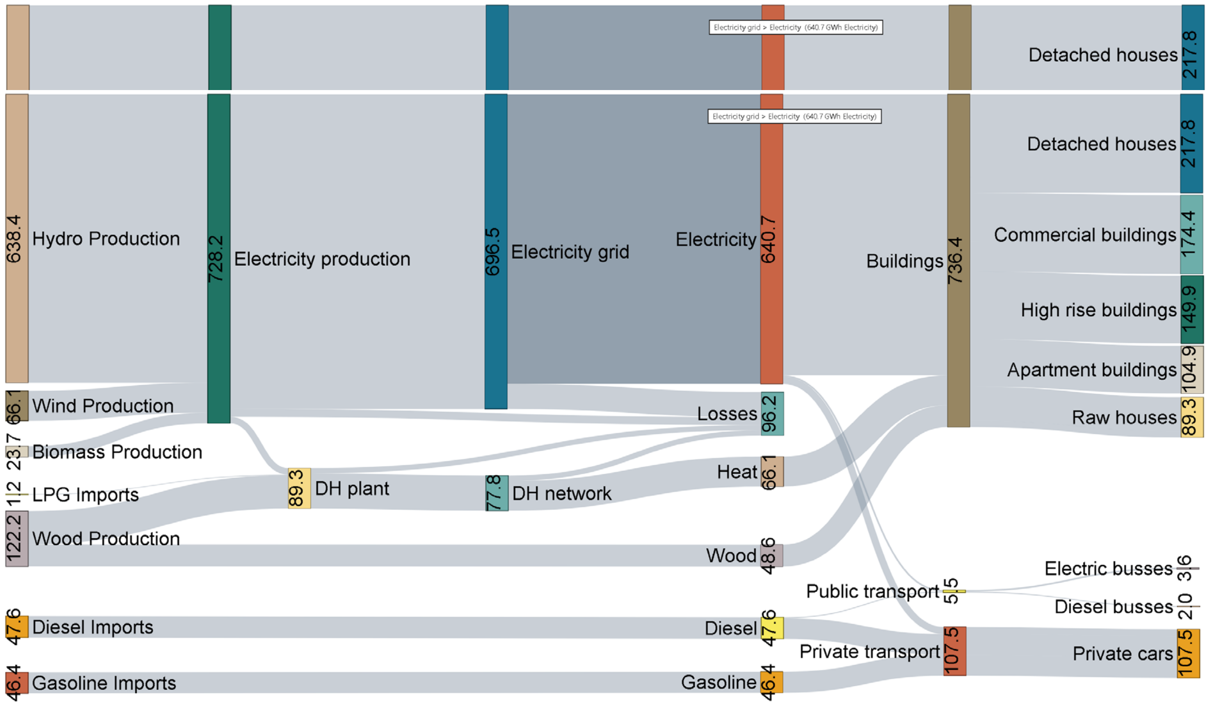

Figure 3. A Sankey diagram representing the current energy flow (2024) from energy resources (left side) to final energy services (right side) in Bodø city. Units are in GWh/year.

3.1.2. BAU scenario - Fuel mix approach for 2050

Figure 4 presents the projected greenhouse gas (GHG) emissions in Bodø arising from the building sector and private transportation over the period 2024 to 2050, under the assumption that historical development trends persist.

The emissions estimates are based on the national electricity production fuel mix and the local fuel mix utilized in Bodø's district heating (DH) plant. The total emissions from buildings and transport sectors are projected to reduce to 18,454 tonnes CO_2-eq by 2050. The most significant reduction in emissions over the forecast period is attributed to the increasing penetration of electric vehicles (EVs) in the private transport sector. However, change in current policies may temper this trend and result with higher emissions from transport.

Conversely, emissions from building operations are anticipated to rise slightly, driven by population growth and the construction of new residential and commercial buildings. Under the MIX fuel approach, achieving net-zero emissions by 2050 is depending upon two critical conditions: the full electrification of the private vehicle fleet and the complete decarbonization of energy production.

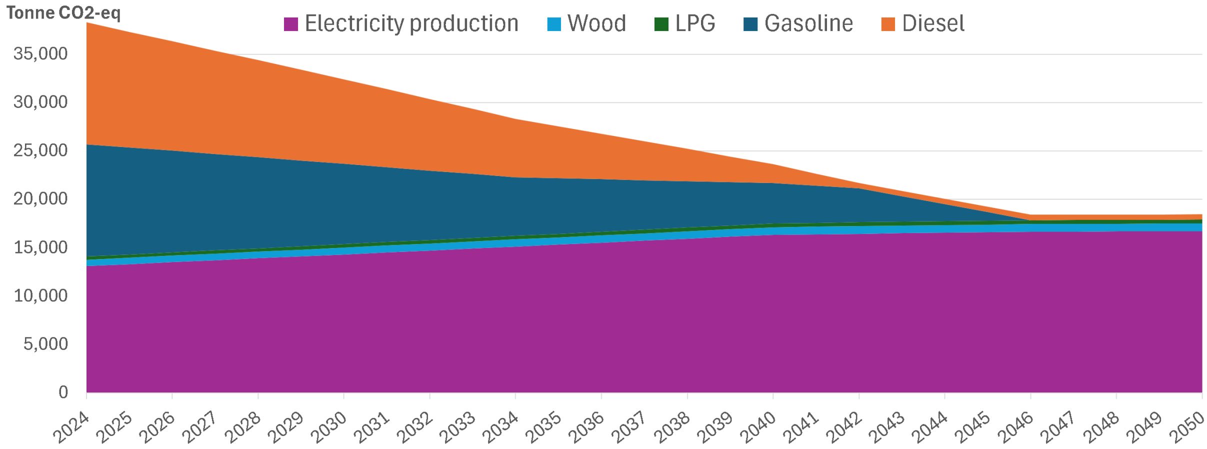

Figure 4. Trends in CO2-eq to 2040 assuming 'Business as usual' scenario with low and high population growths.

Energy-related emissions from buildings currently constitute approximately 36% of Bodø's total greenhouse gas emissions, amounting to 13,717 tonnes CO_2-eq. By 2050, this figure is projected to increase slightly to 16,587 tonnes CO_2-eq, due to population growth, and will account for 89% of the total emissions.

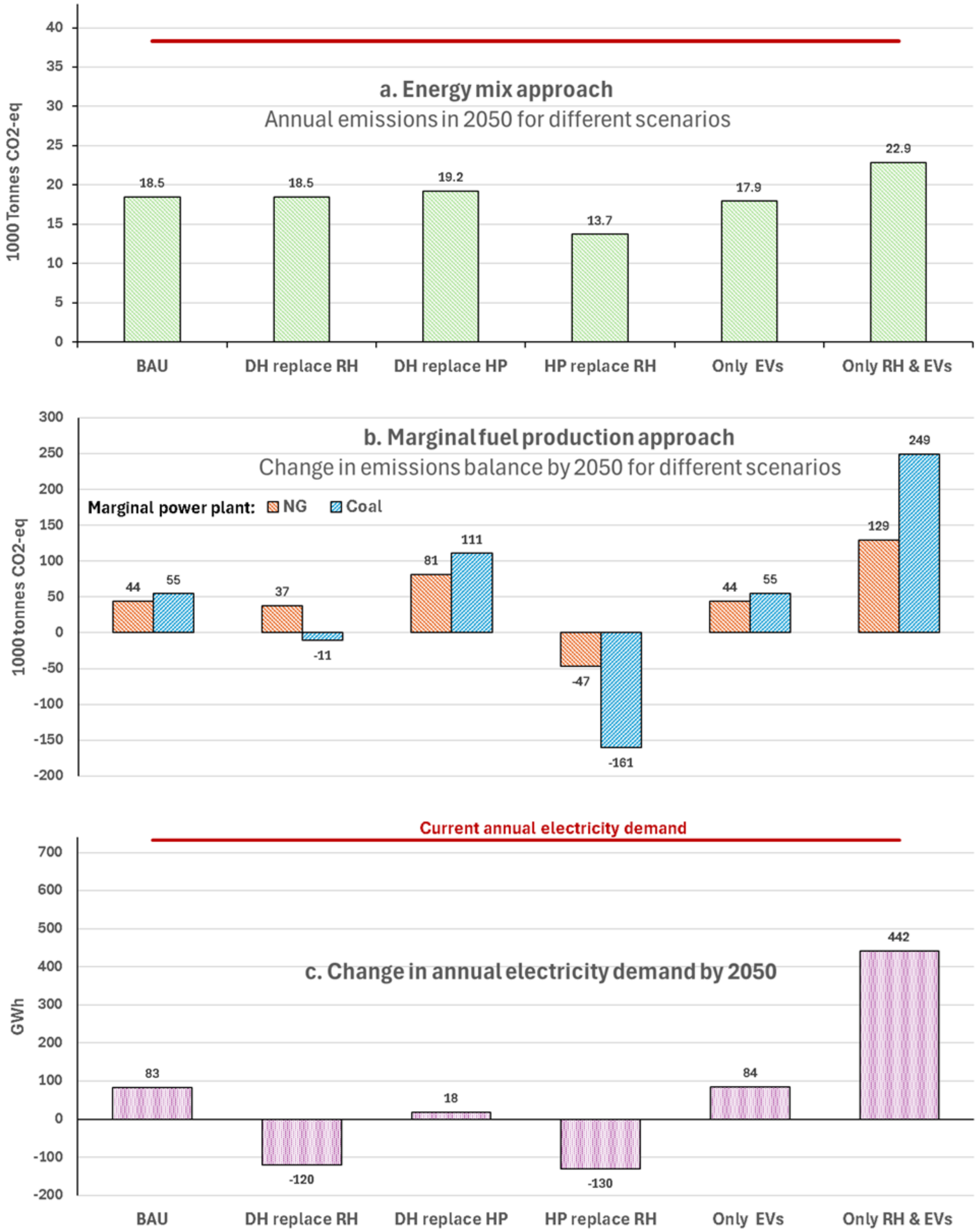

Figure 5. Change in emissions calculated by the energy mix approach (a), by the marginal fuel production approach (b) and change in electricity demand (c) for different scenarios for Bodø in 2050.

Figure 5a presents a comparative analysis of current emissions and projected emissions in 2050, using the fuel mix approach, under different scenarios: the Business-As-Usual (BAU) trajectory and scenarios incorporating heating systems and transport. The findings indicate that connecting buildings to district heating (DH) may result in minor changes to emission levels. Emission may slightly increase if replace heating systems based on heat pumps (HP). Heating systems based on heat pumps (HP) are associated with lower emissions. When these systems are combined with a 100% electric vehicle (EV) fleet, the overall emissions are projected to be the lowest among the evaluated scenarios.

Already the BAU scenario reaches 48% of the current emissions level driven by electrification of the car fleet. The best scenario (HP replaces RH) reaches 36% of the current level. Under this approach, emissions cannot reach zero as long as fossil fuels remain part of the fuel mix. The fuel mix approach suggests that Bodø's energy transition should prioritize electrification in both the building and transport sectors.

3.1.3. Marginal fuel production approach

As Norway's electric grid is interconnected with the broader European grid, a more comprehensive methodology—such as the marginal energy production approach—may be more appropriate. This approach considers the entire European energy system, including fuel substitution effects, thereby providing a more accurate representation of the climate impact of energy choices in Bodø, and is illustrated in Figure 5b.

The results of the marginal fuel production approach revealing a markedly different emissions profile compared to the fuel mix approach. Under this approach, connecting buildings to district heating (DH) leads to emission reductions only when replacing direct resistance heating (RH) systems. In such cases, the potential reduction is on the order of 10,885 tonnes CO2-eq, which is 28% of the current emission level of 38,279 tonnes CO_2-eq.

Among the evaluated heating technologies, heat pumps (HP) emerge as the most effective mitigation option. Depending on the marginal fuel considered, the emission reduction potential can be over 160,670 tonnes CO_2-equivalents, which is more than four times Bodø's current annual emissions from buildings and private vehicles. This significant reduction is attributed to decreased electricity demand, which in turn allows surplus electricity to displace fossil-based marginal generation elsewhere in the European grid. Electrification of the public transport has minor effect on emission levels by 2050 seeing by comparing the EVs and BAU scenarios in Figure 5b.

The RH & EVs scenario may increase the emission level by up to 250,000 tonnes CO_2-equivalents. It is also the scenario with the highest increase in annual electricity demand (Figure 5c), an increase of more than 50% of the current electricity demand. Both district heating (DH) and heat pumps (HP) shows high potential to reduce electricity demand.

Overall, Bodø demonstrates strong potential to achieve net-zero emissions through strategic changes in heating systems, with further reductions possible through energy efficiency measures—though these are beyond the scope of the present study.

3.2. Ålidhem, Umeå

3.2.1 Current state in 2023

Figure 6 illustrate the energy flow from energy resources to final energy services in Ålidhem district. It includes heat and electricity use in residential buildings, energy use in transport both private and public. A total of 82.49 GWh of energy resources is used annually. Approximately 86% of the energy is used in the local DH with biomass and waste as the main energy resources. 11% of the energy resources are used for electricity production, with Hydropower and nuclear as the main energy production technologies. Fossil fuels are mainly used in transport. of the total energy resources, 74% are converted into useful energy in buildings, 9% are used for transport, and the rest (17%) is lost during energy transformation.

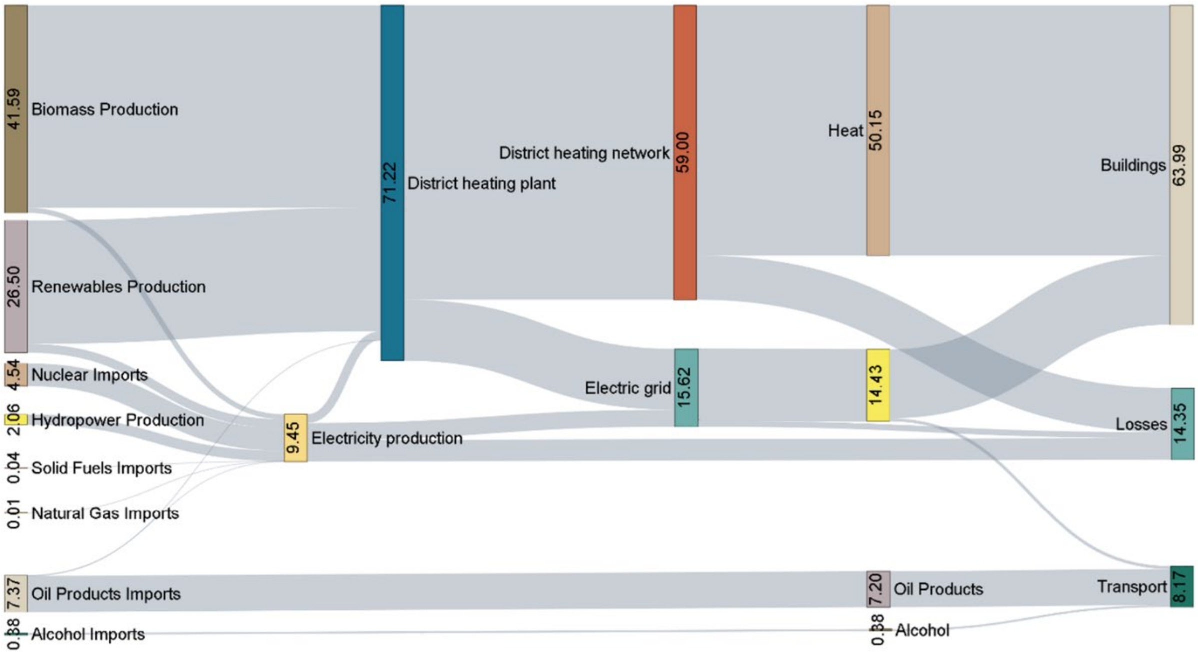

Figure 6. Sankey diagram representing the current (2023) energy flow from energy resources (left side) to final energy services (right side) in Ålidhem district. Units are in GWh/year.

3.2.2. National fuel mix production approach

Figure 7a presents a comparative analysis of current emissions and projected emissions in 2040 under different scenarios: the Business-As-Usual (BAU) trajectory and scenarios incorporating heating systems and transport.

The findings indicate that standard practice of building maintenance may lead to 11% lower emissions in 2040 (BAU). When these systems are combined with national average increase in electric vehicle (EVs) fleet, the overall emissions are projected to reduce by 23% in comparison to current level. PVs installation has no effect on emission reduction as they replace already low emission electricity production. Applying additional insulation to the buildings (Intensive renovation) in addition to standard practice of building maintenance reduces the heating demand by 25%, but only 8% in comparison to the emission in the BAU scenario.

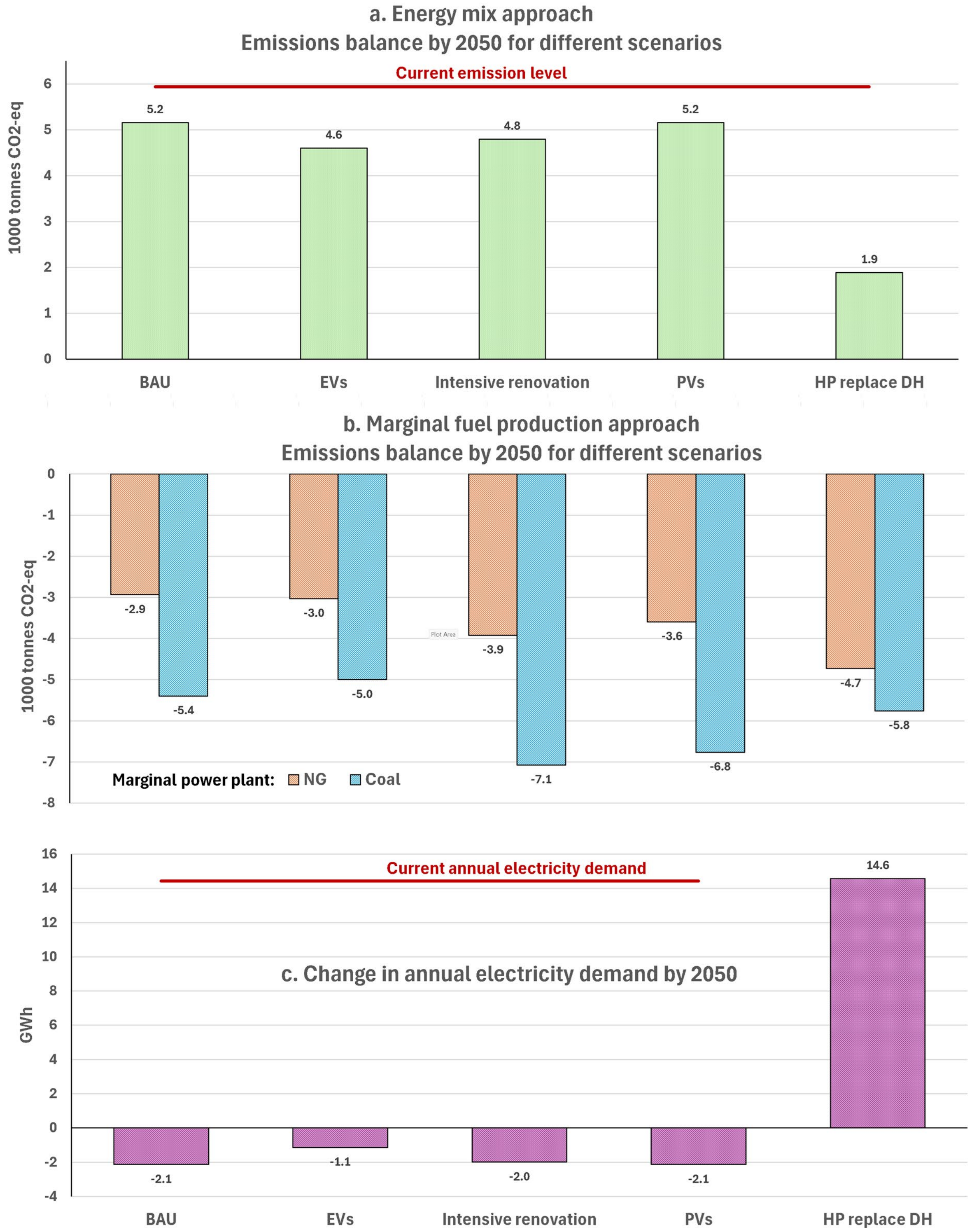

Figure 7. Change in emissions calculated by the fuel mix approach (a), by the marginal fuel production approach (b) and change in electricity demand (c) for different scenarios for Ålidhem district in 2040.

Relacing the district heating network with heat pumps shows significant emission reduction. However, such measure may double the annual electricity demand in Ålidhem as illustrated in Figure 7c. All other scenarios expected to reduce the annual electricity demand by 8% to 15%.

3.2.3. Marginal fuel production approach

Figure 7b illustrates a marginal approach with both natural gas (NG) and coal as the marginal energy production. The results show that emissions reduction is higher if coal is the marginal production technology. Standard maintenance measures in the BAU scenario already show high emission reduction, but to reach zero emissions in 2050 additional insulation is needed in the building (Intensive renovation). Intensive renovation includes added insulation in all the buildings' façade, which is a costly measure. Installation of PVs could also provide the emission reduction necessary to counteract the current emission from the district (5961 tonnes CO_2-eq) if coal is the marginal production technology.

Transport scenario, i.e., electrifying private and public vehicles (EVs) shows only slight difference in emissions in comparison to BAU scenario, and only if NG is the marginal energy production. Transport scenario will increase emission for the case of coal. For the case of NG, as the marginal technology, it is not possible to reach zero climate even if BAU will be combined with installation of PVs transport electrification and applied intensive renovation measures on the buildings.

4. Discussion

This study provides a comparative analysis of energy use and greenhouse gas (GHG) emissions in two distinct and urban contexts—Ålidhem, Sweden and Bodø, Norway, —highlighting the challenges and opportunities associated with transitioning to carbon-neutral districts. Bodø and Ålidhem differ markedly in their energy infrastructure and urban development trajectories. Bodø's reliance on hydropower and its limited district heating coverage contrast with Ålidhem's comprehensive DH network, which integrates CHP technologies and waste-to-energy systems.

A central analytical distinction in this study lies in the application of two Life Cycle Assessment (LCA) methodologies—the fuel mix approach and the marginal fuel production approach—to evaluate greenhouse gas (GHG) emissions in Bodø and Ålidhem. The comparative results reveal substantial differences in emission reduction potential depending on the chosen method, with important implications for urban energy planning and climate policy.

Fuel Mix Approach: Static and Regionally Bound

The fuel mix approach evaluates emissions based on the average composition of national electricity and heat production. In both Bodø and Ålidhem, this method reflects the relatively low-carbon nature of the Nordic energy systems, dominated by hydropower, biomass, wind power, and nuclear energy. Consequently, interventions such as rooftop PV installations or switching heating systems from electric to district heating show limited impact on emissions, as they merely substitute one low-carbon source for another.

Marginal Fuel Production Approach: Dynamic and System-Wide

In contrast, the marginal approach attributes emissions to the technologies most likely to respond to changes in energy demand—typically fossil-based sources such as coal or natural gas. This method expands the system boundary to include the broader European energy market, recognizing that local energy decisions can influence marginal production elsewhere.

Under this approach, the same interventions yield dramatically different results. In Bodø, switching from electric heating to heat pumps significantly reduces emissions, not only due to improved efficiency but also because the saved electricity can displace fossil-based marginal generation in the European grid. The measure, as compared to business-as-usual scenario, could results in approximately 200,000 tonnes more CO_2-eq reduction by 2050.

In Ålidhem, the marginal approach reveals that, if coal is assumed to be the marginal technology, building maintenance and PV installations can together offset nearly all current emissions. If natural gas is the marginal source, the emission reduction is more modest, and even combining all measures—including intensive retrofitting and full transport electrification—does not achieve net-zero.

Implications for Policy and Planning

These findings underscore the importance of selecting appropriate LCA methodologies when evaluating climate strategies. The fuel mix approach may underestimate the true climate impact of local interventions, especially in regions with already low-carbon energy systems. The marginal approach, while more complex, provides a more realistic and policy-relevant assessment, particularly in the context of interconnected energy markets and transitional energy systems.

For Bodø and Ålidhem, the marginal approach highlights the strategic value of reducing electricity demand and prioritizing efficiency, as these actions can have system-wide benefits beyond the local context. It also suggests that PV deployment and electrification should be evaluated not only for their local emissions impact but also for their potential to displace fossil fuels at the margin. As such, the findings underscore the importance of localized strategies, technological choices, and methodological frameworks in shaping effective climate mitigation pathways.

5. Conclusion

This study examined the energy systems and emission trajectories of two urban contexts—Bodø in Norway and Ålidhem in Sweden—through a comprehensive modelling framework incorporating both the fuel mix and marginal fuel production approaches. The analysis highlights the critical role of methodological choice in shaping the perceived effectiveness of climate mitigation strategies in low-carbon energy production systems.

Under the fuel mix approach, both districts appear to be operating within relatively low-carbon energy systems, resulting in modest emission reduction potential from interventions such as rooftop PV installations and heating system changes. This method, while useful for assessing current conditions, tends to underestimate the broader climate impact of local energy decisions due to its static and nationally bounded perspective.

In contrast, the marginal approach reveals significantly greater potential for emission reductions, particularly when fossil-based technologies such as coal or natural gas are considered the marginal energy suppliers. This dynamic and system-wide perspective demonstrates that measures which reduce electricity demand—such as switching to heat pumps or improving building efficiency—can have large climate mitigation benefits by displacing high-emission energy production elsewhere in the European grid.

Policymakers and planners should consider not only the local fuel mix but also the marginal effects of energy demand changes on regional and global emissions. Doing so will enable and support the design of interventions that contribute meaningfully to the broader energy transition.

6. References

[1] European Union, 2024. DIRECTIVE (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast). http://data.europa.eu/eli/dir/2024/1275/oj

[2] Ricardo, 2023. Energy & Environment Assessment of the Long-Term Strategies of EU Member States

[3] Ålidhem (2025). Retrieved August 31, 2025, from https://smartcitysweden.com/best-practice/227/sustainable-alidhem/.

[4] Smart city Sweden (2025). https://en.wikipedia.org/wiki/%C3%85lidhem. Accessed 31 August 2025

[5] Rom2Rio (2025). https://www.rome2rio.com/s/%C3%85lidhem/Ume%C3%A5. Accessed 31 August 2025

[6] City energy analyst (2025). https://www.cityenergyanalyst.com/ Accessed 31 August 2025

[7] SEI (2025). https://www.sei.org/tools/leap-low-emissions-analysis-platform/ Accessed 31 August 2025

[8] Polysun (2025). https://www.velasolaris.com/en/products/polysun-spt/

[9] [ref. Excel file] from Bodø

[10] Statistics Norway (2024) Energy consumption in households. www.ssb.no. Accessed 05 September 2025.

[11] Lindberg, L., Olofsson, T., Vesterberg, J., Andersson, S. Reflections on sustainable Ålidhem - A case study in Swedish municipal public housing refurbishment, *Prop Manag.* **36**, 203-220 (2018).

[12] Levander, T., Stengård, L. Measurement of cold- and hot water consumption in 44 households [Swedish], *Statens Energimyndighet*, Eskilstuna (2009).

[13] SVEBY, Brukarindata bostäder, *SVEBY - Branchprogramet för energi i byggnader*, Stockholm (2012).

[14] Kommuneprofilen (2023) Samferdsel (Transportation). https://www.kommuneprofilen.no/. Accessed 05 September 2025.

[15] Umeå open data https://opendata.umea.se/

[16] The Swedish Agency for Economic and Regional Growth (database: pipos.se)

[17] Personal communication Umeå Municipality

[18] Resvanor I Umeå så reste vi i kommunen hösten 2022

[19] Danish Energy Agency, Technology Data for Energy Plants for Electricity and District Heat Generation, Danish Energy Agency, 2022, web-accessed at: https://ens.dk/en/our-services/projections-and-models/technologydata/technology-data-generation-electricity-and

[20] Energiföretagen, 2023. Överenskommelse I värmemarknadskommittén 2023. Web-accessed: https://www.energiforetagen.se/statistik/fjarrvarmestatistik/miljovardering-av-fjarrvarme/

[21] Personal communication Umeå energy

[22] Personal communication Bodø Municipality

[23] Energy system of Sweden, The International Energy Agency (IEA). Web-accessed at: https://www.iea.org/countries/sweden (Accesses at 2025)

[24] Energy system of Norway, The International Energy Agency (IEA). Web-accessed at: https://www.iea.org/countries/norway (Accesses at 2025)

[25] Mattsson, M., Danielski, I., Olofsson, T., & Nair, G. (2025). Archetypes-based calibration for urban building energy modelling. *Energy and Buildings*, 115843.

[26] Statistics Sweden (2023) Traffic analysis. Web-accessed at: https://www.scb.se/ (Accessed 05 September 2025)