

Greenhouse gas emission accounting at urban level: A case study of the city of Wrocław (Poland)

Izabela Sówka, Yaroslav Bezyk*

Unit of Ecologistics and Environmental Risk Management, Faculty of Environmental Engineering, Wrocław University of Science and Technology, Wyb. Wyspiańskiego 27 St., 50-370, Wrocław, Poland

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ABSTRACT

The paper analyses the building process of a GHG emissions inventory, which would likely enable more strongly cities to manage their efforts and set realistic targets for emission reduction. The work includes the determination of GHG emission estimation tools and approaches used for estimation of key sources of these emissions at the local level. The actual task is the determination of major GHG emitting sectors including the key characteristics of these emissions sources at the local level, establishing targets for emissions reductions at Wrocław urban area, Poland. The sectoral GHG emission trends in the selected urban area including a comparison of carbon dioxide (CO₂) emission level with national inventory data are presented. The total GHG emissions from Wrocław municipality in 2013 were 7.2 percent lower than those in 1990. Energy consumption is a major contributor of emissions responsible for 63% of citywide CO₂ through the consumption of electricity and district and individual heating using coal and natural gas energy sources. The proposed data structure is connected in an informative Sankey diagram for all anthropogenic GHG emissions occurred in Wrocław municipality in 2013. In order to determine the City progress towards urban carbon neutrality, reducing emissions 25% by 2020 and 80% by 2050, as well as the future risks and impacts of GHG emissions on climate change the 'business as usual' final energy consumption and emission scenarios are provided.

1. Introduction

Urban areas as a home over half of the world's population who are responsible for approximately 60–70% of anthropogenic greenhouse gas (GHG) emissions (Hot Cities, 2011), 17–32% of GHG emissions are associated with food production cycle and consumption (Bellarby et al., 2008); 33–35% of GHG emissions are related to the energy use in settlements (Allwood et al., 2010) and this share will only increase in future by the current trends of expanding energy sector (IEA, 2015). Accordingly, it is difficult to overestimate the importance of cities for mitigating climate change: territories of urbanization play a major role in reducing GHG emissions and mitigating climate change.

The United Nations Climate Conference (COP21) held in Paris highlighted the greater role of city-level actions in reducing global energy demand and limiting GHG emissions. One of the memos from COP21 is a greater realization of the cities importance in fighting climate change issue, especially result-oriented bottom-up initiatives (Leal-Acas, 2012) from urban territories, including creating citizens' environmental awareness (Brondizio et al., 2015; LSE Cities).

Effective action to reduce GHG emissions at the local level,

however, depends on having access to good quality data on emissions. Climate action planning begins with creating a high-quality of GHG inventory. As a result, municipalities are required to have available tools for designing a GHG emissions inventory. Appropriate techniques for developing regional approaches to GHG emission inventory need to take into account the features of different areas, where certain types and qualities of fuels with a defined character of spatial development in consumption structure dominates (GRIP, 2009).

The accounting process of urban emission needs better-integrated frameworks because the city estimation actions often are non-systematic and also limited to selected regions and emissions into mostly CO₂ equivalents. That is why the well place-based GHG inventory comparisons are difficult. The GHG emissions calculation results for urban areas differ widely for the accounting methods, scope and sources of emission, allocations of embodied emissions, local policy and time framework of inventory control (Brondizio et al., 2015).

In order to assess and reduce the overall GHG emission level from an urban area, it is necessary to identify of all activities and processes, which generate of these emissions. The fact of this matter is that GHG inventory gives an opportunity to get wider knowledge about spatial

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* Corresponding author.

E-mail addresses: izabela.sowka@pwr.edu.pl (I. Sówka), jaroslav.bezyk@pwr.edu.pl (Y. Bezyk).

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emission processes in the sectors of the economy not only at the national level but also at the level of administrative units. The local inventory data provided by effective GHG emission inventory tools adapted to full regional perspective can be used to improving energy efficiency and identifying innovative sectoral and cross-sectoral plans for GHG emissions reduction in selected area.

2. Materials and methods

The emission inventory from 1990 to 2013 for urban area was verified. The GHG emissions estimation process in the city scale is standardized according to the methodological framework of the Intergovernmental Panel on Climate Change (IPCC) as well as the requirements of a network of local initiatives such as ICLEI – Local Governments for Sustainability and the Covenant of Mayors co-operation group. Basic information about activity data on different emission source categories is mostly gathered in numerous official polish public statistics (*Statistical Yearbook*, 2015). Input data includes energy statistics, industry statistics, transport statistics, agricultural statistics, also based on emission factors for a given activity level under a given set of operating conditions of each emission sector in a given year. The activity data that are not available in public statistics were received upon request or developed out by a number of scientific institutions as well as individual experts (Institute of Transport, Institute for Ecology of Industrial Area, Energy Market Agency, and Municipal Office of Wrocław).

The national emission inventory database of Poland is run by the ‘National Centre for Balance and Emissions Management’ (*KOBIZE*, 2015) and results from inventory data of the city of Wrocław are defined in “Low Emission Economy Plan for Integrated Territorial Investment at Wrocław Functional Area” (*Low Emission Economy Plan*, 2015). The Poland's National Centre for Emission Management (*KO-BiZE*) is responsible for the operation of the national system of emissions balancing and forecasting, which includes collecting data on the volume of GHG emissions, processing, evaluating, reporting and predicting future trends in GHG (*KOBIZE*, 2015). ‘Low Emission Economy Plan for Integrated Territorial Investment’ is a new tool introduced in the relevant national regulations and urban strategies that lead to the low carbon economy, resource efficiency in all sectors and climate change adaptation, focused on integrated territorial approach within a given economic, environmental, social situation on the ground (*European Commission*, 2003; *URBACT*, 2014).

The city of Wrocław, located in west-south Poland (*Fig. 1*), was used as a selected study site for analysis of the process of preparing GHG emission inventory and developing local plans to support local emission reduction initiatives. Wrocław was chosen due to its increasing number of energy efficiency improvement initiatives, high-level activities for GHG emission reduction in different economic sectors and programs oriented to changing citizen's behavior with regard to energy usage in the residential sector. The municipality of Wrocław has specific experience in Integrated Development Programs in the field of climate change action plans and low-carbon economy initiatives: a system of subsidies to eliminate coal heating, developing public transport infrastructure and a concept of primary routes network bicycle. (*Commune of Wrocław*, 2009).

With a population close to 630.000 a land area of 292.92 square kilometers and a metropolitan figure well over a million, Wrocław is the fourth largest cities in Poland. City also serves as the administrative, socio-economic and cultural hub, with a high level of all manufacturing activities. The largest service industries in Wrocław are: financial services, retail and real estates and the production industry includes buses, trams, railroad cars, home appliances, chemicals, and electronics (*Statistical Yearbook*, 2015).

The municipality of Wrocław generates emissions inventory data using the international and European protocol standards. The average contribution of main source categories of GHG emissions in the city of

Wrocław is classified according to GPC Protocol scopes standard, Sustainable Energy Action Plan (SEAP) and International Council for Local Environmental Initiatives (ICLEI) methodologies (*SEAP*, 2010; *ICLEI-CACP*; *ICLEI-HEATplus*). According to the policy framework for summarizing the complex information of the supply data, material, and energy efficiency and reducing final energy demand and carbon emissions, in the study, the Material Flow Analysis (MFA) method was adopted. The Sankey diagram (*SankeyMATIC*; *Vigon et al.*, 1993) of energy flow and related CO₂ emissions in the city of Wrocław is provided to a deeper estimation of the total energy sources consumption and further possible efficiency improvements and GHG emission reduction measures for Wrocław Municipality. In a Sankey diagram, energy (fuel, heat, and electricity) derived from Statistical Yearbook of Wrocław City, polish energy statistic is converted into carbon dioxide emission flow for 2013. The GHG mitigation scenarios from the business-as-usual plan that cover various energy demand and supply mechanisms are developed for a study period of 40 years (2010–2050) based on is based on the Energy Policy of Poland until 2030 (*Ministry of Economy of the Republic of Poland*, 2009), including a forecast of demand for final energy by sectors and the share of different fuels in the structure of consumption.

3. System boundary and GHG accounting methodology

Monitoring and estimation of baseline and event-driven greenhouse gas emissions from different sectors at urban area are based on variety advanced tools already existing in different European countries and worldwide. Depending on the purpose of the GHG measurement, different methods may be used. Methodologies that can be applied to quantify greenhouse gas emissions are: the emission factor-based method (a coefficient which quantifies the emissions per activity), the mass balance method (Input = Output + Emissions), the predictive and continuing emissions monitoring system (comprises elements of the direct measurement and the calculation based approach) and direct measurement of GHG emissions (accurate and real-time data) (*Bader and Bleischwitz*, 2009). For the inventory process, which aims at gathering data on a wide range of GHGs and various emission sources, the emission factor or mass balance method is widely used.

The inventory covers following greenhouse gases according to the Kyoto Protocol: carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), HFCs (hydrofluorocarbons: HFC-23, HFC-32, HFC-43-10mee, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea), PFCs (perfluorocarbons: perfluoromethane - CF₄, perfluoroethane - C₂F₆, perfluorobutane - C₄F₁₀) and sulphur hexafluoride (SF₆) (*Kyoto Protocol*, 2002).

According to the United Nations Framework Convention on Climate Change (UNFCCC) the GHG inventory is an assessment of anthropogenic emissions of the most relevant greenhouse gases within a certain region and period of time (*UNFCCC*, 1992). Guidance for national accounting GHG emissions, also in calculations for city activities data, is provided by the detailed methodological framework of Intergovernmental Panel on Climate Change (*IPCC*, 1996). Emission factors specific to the urban area are often based on the recommended for country-level IPCC Tiered (referred Tier 1, 2 data source) measuring rules (*IPCC*, 2006). The accuracy of the emission inventory, based on emission factor approach, depends on the precision of the emission factor value as well as on the accuracy of measured activity data (GHG).

With regards to GHG emissions measuring for communities often is used the concept of ‘scope’ allocations. The GHG Protocol standard for cities known as ‘Global Protocol for Community-Scale Greenhouse Gas Emission Inventories’ (*GPC*, 2014) recommends to group emissions in three “scopes” depending on where they physically occur (within and without city boundaries). In the GPC Protocol methodology basically are used three boundaries, which group all GHG emissions in different scopes (scope 1, 2, 3) based on where they occur (*GPC*, 2014):

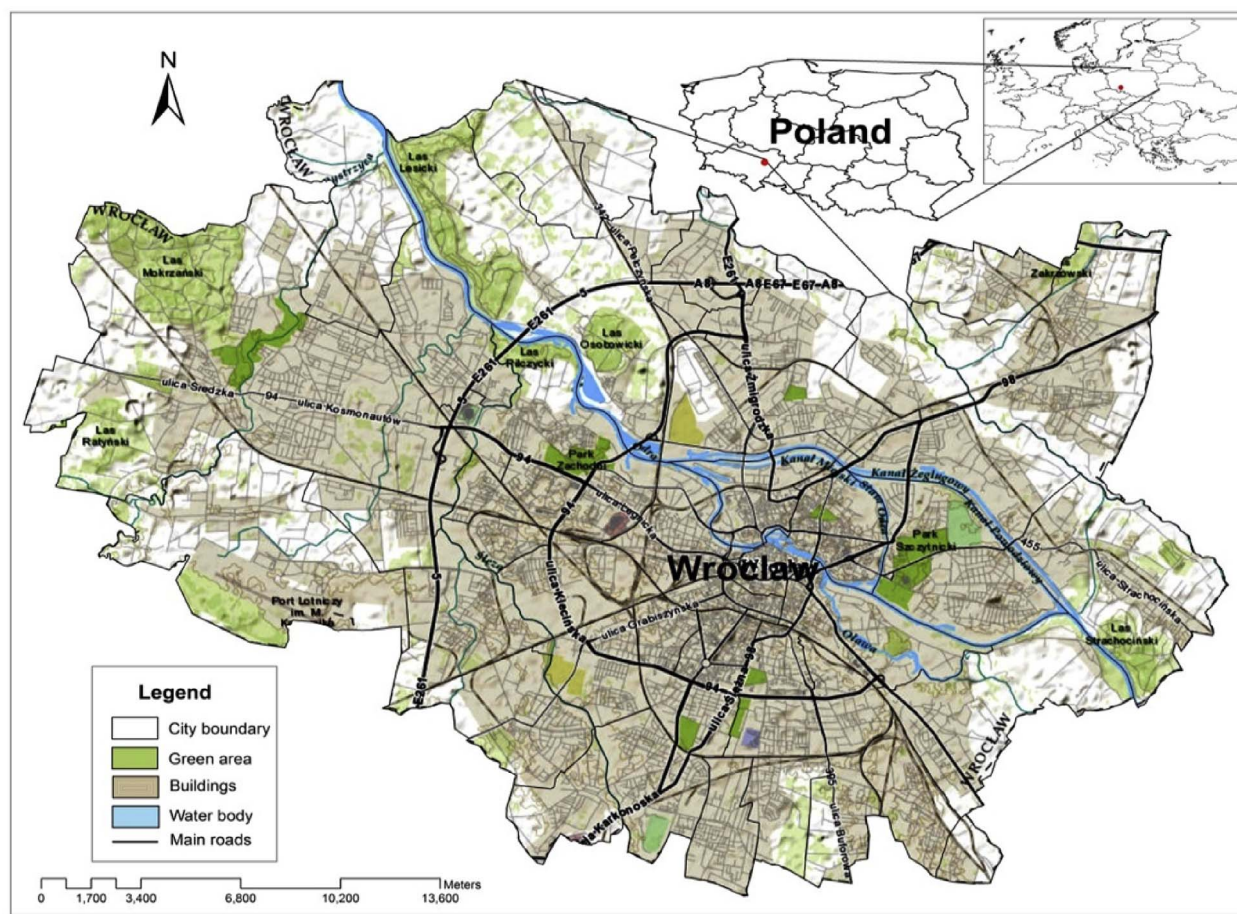


Fig. 1. Location of study area (Wrocław, Poland). Source: base map source: OpenStreetMap.

- *Scope 1* includes all GHG emissions from sources within local authority (direct emissions that occur inside the city geographic boundary);
- *Scope 2* covers all GHG emissions occurring on and outside local authority (indirect emission caused by the consumption of electricity, heat or steam);
- *Scope 3* includes all GHG emissions that occur outside local authority (indirect emission as a result of activities of local actors, e.g. electricity transportation related activities).

The critical importance in GHG emission inventory process is to have a detailed overview and allocated urban emissions in different sectors. Many current activities are producing GHG emissions, e.g. stationary energy, transportation, industrial processes and product use, waste, agriculture, forestry, and other land use (AFOLU) and other indirect emissions (GPC, 2014). Attributing anthropogenic carbon concentrations to a specific source is challenging because emissions varies depending on type and location, technology type and operational practices, meteorological conditions, time framework, (U.S. Environmental Protection Agency, 1995). Then, the exact amount of GHG emissions from selected sources at urban area can be hard to pinpoint, and some sources are better known than others. With pure data of actual field emission measurements, individual inventories can use data for a specific sector from national statistics if the relevant data are difficult to obtain at local level and could be scaled. The rule is that scaling data from national GHG inventories can be applicable within local authority if data for a selected sector are broken down from the national GHG inventory and sector contribution is not considerable in overall emissions from the city (Bader and Bleischwitz, 2009).

The accuracy of GHG emissions calculations depends on the

precision of emission factors that are estimated for a certain region and category of emission origins. An emission factor is defined as the average emission rate of a given GHG for a given source, relative to units of activity (UNFCCC, 1992). The city-specific emission factors give an opportunity to get wider knowledge about spatial emission processes in the selected sectors of the economy or at the level of administrative units and divided source of emissions (Wintergreen and Delaney, 1406).

The inventory tools and methodologies furthermore differ with how cities allocate emissions to the territory where they were emitted (Nuorkivi, 2010). Ideally, whenever the GHG emissions are to be expressed in ratio performance indicators (emissions per geographic area, per unit of energy produced, per person, Gross domestic product (GDP), etc.), in total city's carbon emission inventory should be included the account of the imported and exported emissions (from energy consumption, product use and waste production) (Bellassen et al., 2015; Climate Alliance). For instance, in city's emissions accounting and reporting practices it should be clearly distinguished whether only the direct (sources located in cities) and/or also indirect (upstream) emissions are calculated (clear measurement frameworks), what has major consequences for the results of the inventory process.

4. Results and discussion

4.1. Analysis of Wrocław greenhouse gas emissions inventory

The local inventory data for Wrocław urban area (Low Emission Economy Plan, 2015) presents the total GHG emissions level in 2013 at 4113.77 kilotons (kt) of CO₂-eq emissions (6.52 Mg CO₂-eq per capita). Between 1990 and 2013 total GHG emissions in Wrocław decreased by 7.2% (317.1 kt of CO₂-eq) largely through reduced consumption of

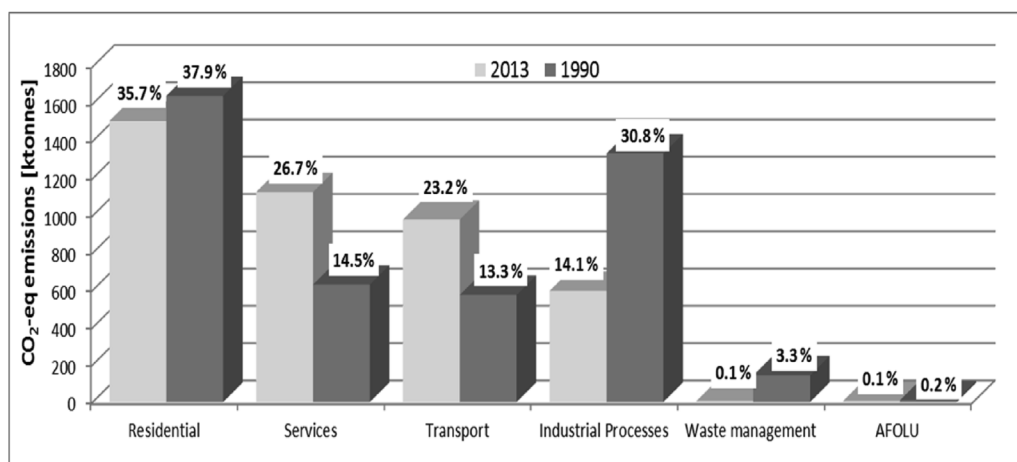


Fig. 2. Anthropogenic greenhouse emissions by sectors in Wroclaw urban area (2013 & 1990).

district heat, decreased emissions in the industry sector, waste and in agriculture, forestry and other land use (AFOLU) sector. Over 85% of overall GHG emissions amount are resulting from energy consumption in city (see Fig. 2). Combustion of fossil fuels for electricity and heating purposes makes up for 3613.1 kt of CO₂ of the whole emission level. Responsible for the issue was primarily residential sector (over 37.9% of total emissions) through the use of electricity, district heating and coal in 2013. For instance, if compare this value to Poland's national emission level, we can see that rate of energy use in households and services in Poland is equated to 23–24% of country's total emissions in 2013. The share of polish energy industries is more than 52% of entire emissions amount (KOBIZE, 2015).

The main fossil fuels responsible for GHG emission from Wroclaw mainly are coal and natural gas (commerce, household, and industrial needs) as well as diesel and petrol (fuel used in transport). Emissions from all transport activities in Wroclaw increased almost twice relative to 1990 (from 574.2 to 978.5 kt of CO₂-eq) due to the raise the amount of individual transport and outdated car fleet. It amounts to 24% of total GHG emissions from city in 2013 and while in national inventory its' part lies between 13 and 14%. The indicated changes generally are responded to the increasing life level and mobility needs of people and demand on goods and services in Poland in last decade (Krzeszowiak et al., 2015).

In contrast, greenhouse gas emissions contribution from the industrial processes in the city scope were much higher (near 14.1%) than mentioned sector's rate of GHG emissions in national scale (near 6–7%). Among the remaining 596.1 kt of CO₂-eq emissions in city contribute mainly industrial processes in 2013 and 1432.9 kt of CO₂-eq in 1990. At the national level, agriculture and forestry were being responsible for 9–11% of greenhouse gas emissions, in case of the city less than 1%. As it can be seen (Fig. 2), the annual mean of emissions from waste management in Wroclaw in 2013 decreased in three times compared to the base year. In 1990 the waste and wastewater treatment sector was causing up to 3.3% of the total CO₂ emissions. Substantial changes mainly were caused by the variances in managed municipal landfills, application of the new waste treatment technologies (use of methane removal in landfills) and implementation of the new legal regulations for waste management in Poland (Low Emission Economy Plan, 2015; KOBIZE, 2015).

Responding to the Wroclaw's inventory results, the proposed data structure are connected in an informative Sankey diagram for all anthropogenic GHG emissions occurred in Wroclaw municipality in 2013 (Fig. 3). Represented Sankey diagram “Wroclaw energy flow and related carbon dioxide emissions” is relevant to interactions between human demand for energy sources and anthropogenic GHG emissions (classifications for determining urban sectors of the economy). Data for the diagram is gathered from the greenhouse gas inventory and variety

of energy use statistics for Wroclaw urban area. The flow visualization in Sankey diagram is grouped according to existing Baseline Emission Inventory (BEI) scenario (final energy consumption and CO₂ equivalent emissions) represented in “Low Emission Economy Plan for Integrated Territorial Investment at Wroclaw Functional Area” (Low Emission Economy Plan, 2015).

The Sankey diagram consists two main parts defined by the energy demand chain structure and related emissions. The final energy consumption by the end users on the left part of diagram eventually drives to the emissions from the inventory sectors on the right as result of conversion energy amount by carriers (coal, natural gas, petroleum and less than 8% from renewables). The consuming sectors (settlements, transportation, non-energy industry etc.) lastly are divided into sub-groups, offering one more level of detail. The width of the arrows is proportional to the flow quantity of energy also emissions through a system. The quantities labels along the Sankey arrows show the average flow value. The vertical solid lines represent that energy related data (GW*h per year) on the left is converted into emission numbers in equivalent units (1000t CO₂-eq per year) on the right side within selected consuming sectors. The second part of the Sankey diagram is a summary of greenhouse gas emissions.

The GHG emissions in the Wroclaw municipality are counted using territorial-based approach. The inventory covers an area of the community, but also is extended by emission rate from electricity and heat produced outside the municipal boundaries (scope 2 emissions), and indirect emissions from the processes of waste generating (scope 3 emissions) (Low Emission Economy Plan, 2015; GPC, 2014). Major electricity producers at Wroclaw Municipality area in 2012 were able to cover about 60% of city electricity demand, including losses in a network (Updating the assumptions, 2012). In such case, the red arrow in the Sankey diagram (focuses on electric energy) is blown up and forms part of the country energy mix (variety of fuel sources for electricity generation in a state). It is important to note, the Polish energy sector is historically based on fossil fuels. In polish energy mix is dominated coal and lignite, which produce nearly 90% of Poland's electricity (Poland Energy Report, 2012).

Depending on the goal, the accounting for current country energy mix is often used to enable a comparison of the balances in the power generation between the different municipalities and country in general. In addition, the calculating country energy mix includes energy territorial mix as a part of the whole system. In order to maintain comparability of the results of emission inventories across the country, it was adopted national emission factors. Reference rate per unit emission of carbon dioxide in the production of electricity, determined from National Centre for Emissions Balancing and Management (KOBIZE, 2015), was 831.50 kg CO₂/MWh in 2013 (Audytoenerg.pl). At the same time, the GHG emissions resulting from the production of electricity



and heat network are assigned to end users of fuels and/or their energy consumption in the territory (Poland's informative inventory report 2015, 2015). The data quality of a balance is obtained by the proportion of final energy carrier multiplying the total energy consumption, later these calculated values are summed up for all energy sources. When heat is provided as a co-product of combined heat and power (CHP) plants, the exergy allocation is used (Empfehlungen zur Methodik, 2014; WBCSD/WRI, 2006).

Coal and natural gas are used mainly in Wrocław city for cogeneration in CHP units and in private boilers (grey and blue arrows in the Sankey diagram); also natural gas is used for preparing food in commercial and private households. Power from CHP and electricity from the grid (country energy mix) follow to the end-consumers. Produced heat is used directly for heating in private and public buildings (violet arrows in the Sankey diagram). The generated electricity, as well as other energy carriers, is further broken down in the flow arrows into end-user sectors. Losses of electricity generation and distribution out at the CHP node are shown as a grey arrow. Eventually, the cost for generated energy for each energy user categories in the Sankey diagram is assessed as the CO₂ emissions (depicted in the grey flow lines in the Sankey diagram).

Energy consumption and emissions from transport sector have been calculated according to the territorial principle. These are based on the travel and transport services in both local and transit transport crossing the boundaries of the municipality. The method adopted for estimating emissions corresponds to average in-use fuel consumption values for each vehicle category (motorised private and public transport) and the average annual vehicle-kilometres driven within the municipality (Low Emission Economy Plan, 2015). For instance, the petroleum fuels used for transportation include gasoline, diesel, and liquid petroleum gases (represented in orange flow lines) makes up for 883.3 kt of CO₂-equivalent emissions. The reference to space 'territory' is chosen because of the aim of actions within the community.

The magnitude of the Agriculture, Forestry and Other Land Use (AFOLU) emissions from cities is usually small or negligible (typically contribute less than 1 percent to the total emission from the urban areas in Europe (Hoornweg et al., 2011)), but this contribution is quite specific. The emissions from AFOLU mainly cover the agricultural activities and livestock; however emission part from the fuel consumption is also included. This share is negligible compared to CO₂ emissions for the energy sector, but has been quantified because the urban vegetation sequesters. In total, the AFOLU emissions are corrected by carbon sequestration in the sector. The AFOLU emissions in Wrocław have decreased significantly in the last decade. The Wrocław's net carbon sink makes in total near 5.2 kt of CO₂-eq absorption (near 0.13 percent of total city emissions) and the terrestrial carbon stocks also can be increased by further sequestration in soils and biomass.

It is worth noting that energy industry included into the EU Emission trading scheme (ETS) scheme is cut off from energy input stream and corresponding emissions in the Sankey diagram (European Commission, 2015). Total emissions from these installations amounted to 1475.1 kt CO₂-eq in 1990 and 1197.2 kt of CO₂-eq in 2013 (Low Emission Economy Plan, 2015). In general, the Covenant of Mayors' (CoM) recommendation is that the EU ETS industry should be excluded from the city emission inventory (Covenant of Mayors for Climate and Energy, 2016b). Orientation is on the final energy consumption side and on the sectors upon which the local authority has an impact such as buildings and facilities managed by the local authority and also the residential, the transport (commercial and public) sectors (Covenant of Mayors for Climate and Energy, 2016a).

The Baseline and Monitoring Emission Inventories (BEI) elaborated in the frame of the cities' commitment to CoM are not meant to be exhaustive inventories of all emission sources on the territory. Therefore, the local authority can decide to include emissions from other sectors such as the non-ETS industrial sector, agriculture, forestry, and fisheries or sectors not related to the energy consumption

(Covenant of Mayors for Climate and Energy, 2016a; German Informative Inventory Report, 2016). For instance, emissions from industrial plants not included in EU ETS are often reflected in the BEI, because of the implementation measures to improve energy efficiency in these plants in the framework of cities' Sustainable Energy Action Plan (SEAP, 2010; Westner and Madlener, 2011).

The composition of the primary energy entering the energy system of the city of Wrocław, and where primary energy is used, as consumption by specific sectors of the economy and to the current trends of GHG emissions in Wrocław municipality, represented in the interactive Sankey diagram, could be the quite significant source for further analyzing Wrocław's energy-related activities and to give recommendations towards GHG emission accounting and establishing targets for emissions reductions at Wrocław urban area.

4.2. Recommendations for reducing carbon footprint in the municipality of Wrocław

Analysis of current energy consumption level in the city of Wrocław and design of future final energy consumption paths in Poland by 2050 have been used to investigate the expected trends in energy demand and consequences CO₂-eq emissions in Wrocław up to 2050. The future state is described under two alternative pathways: if current trends in energy use and traffic continued, in which the chosen development in the future is mapped as 'business as usual' (BAU); and if additional reduction effects can be achieved by measures at the city, known as Low Carbon Economy Action Plan or Low Growth Emission Scenario.

The global scenarios of low carbon development in urban area are mainly based on energy-efficiency savings in energy-intensive manufacturing in the district and behavioral change in settlement areas; however given a limited view of the future spatial requirements changes and extension of urban territory (Kemp-Benedict et al., 2002). The Low Growth scenario is dependent on the optimal implementation of the environmental protection strategies, which focused on reducing CO₂ emissions by 80% by 2050 (the adopted base year 2005) (European Commission, 2013). In this scenario, the end user energy consumption decreases by half. The emission reduction effect is largely due to efficiency improvements in manufacturing, the use of combined heat and power (CHP), solar, wind and bioenergy, less final energy consumption in residential and service sectors, declines using private vehicles per head of population (Auckland Council Plan, 2011; European Commission, 2013).

While the country-specific emission factors for final energy are used in calculation Wrocław energy mix and further GHG release (does not take into account seasonal variations in electricity supply) is assumed to disaggregate information through Poland's Forecast of Energy Fuel Mix until 2050 (Conclusions from the analysis, 2014; Ministry of Economy of the Republic of Poland, 2009). It can be the best data option to design future energy consumption paths in Wrocław by 2050. Poland's energy policy contains guidelines how the country's energy demand is to be developed. The energy requirements for 2050 should decrease by reducing primary energy consumption and electricity consumption, development of low emission technologies, enhancement share for renewable energy sources (Conclusions from the analysis, 2014; Ministry of Economy of the Republic of Poland, 2009; Poland Ministry of the Environment).

The BAU final energy demand scenario for Wrocław is built on the Energy Policy of Poland until 2030 (Ministry of Economy of the Republic of Poland, 2009), including structural changes in the energy sector and the structure of consumption. Economic growth in Poland accompanied by the increasing share of the energy consumption at 8.7% between 2010 and 2030 (energy is produced mainly from fossil fuels). Development of the country's renewable energy sources should reach the share of around 15.5% in energy generation in 2020 (Energy Sector in Poland, 2013). The projected final energy consumption and CO₂ emissions scenarios for Wrocław urban area are shown below

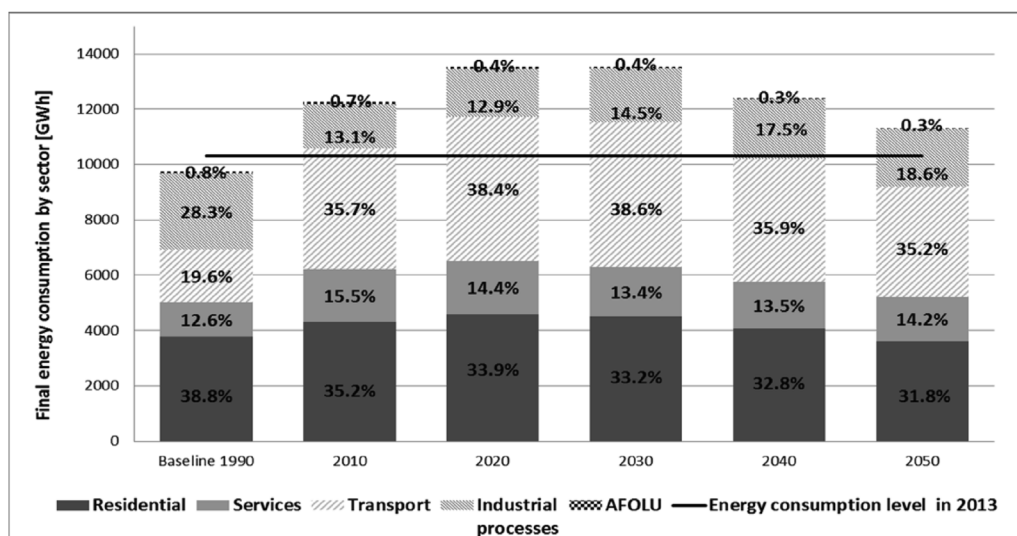


Fig. 4. Final energy consumption scenarios for Wrocław vs. baseline year 1990: in the case of 'no climate action (BAU)' scenario, (GWh), (given percentages on chart bars is a share of each source in the relevant year).

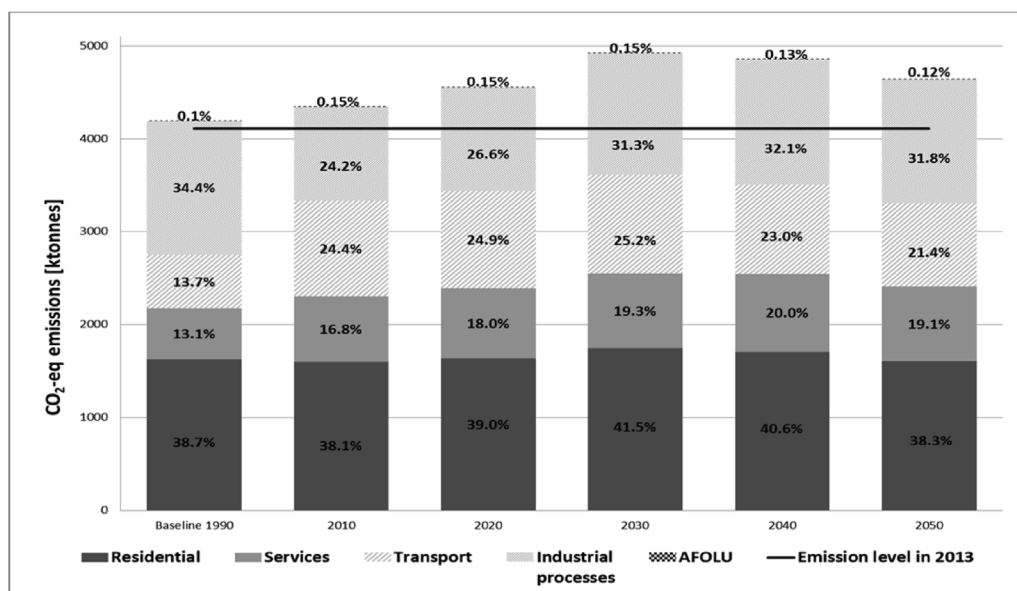


Fig. 5. Changes in GHG emissions in Wrocław, 'no climate action (BAU)' scenario 2050 vs. 1990, (kt of CO₂-eq), (given percentages on chart bars is a share of each source in the relevant year).

(Figs. 4 and 5).

These BAU scenarios were calculated by evaluation probable fuel mix until 2050, energy level requirements in the industry, buildings, services, in transport sector based on forecasted traffic growth, with an assumption of non-significant efforts made to reduce emissions. The final energy consumption in the BAU scenario in Wrocław is projected on the level 13539 GWh in 2030 is increased by 10.4% compared to 2010 and decreased by 7.7% in 2050 according to 2010 (forecast level in 2050 is equal 11318.6 GWh). The electricity demand in total energy consumption would increase by nearly 36.3% up 2010 level by 2030, further after 2030 will start decreasing of mean by 1.4%. The annual growth in energy demand from 2010 to 2030 would increase in average by 1.7% per year, in the following sectors: residential 2.9%; services 2.2%, transport 3.3%, industry 2.5%. A growth would continue until a significant improvement in the energy intensity in the industrial and household sectors, decreased level of car use. According to the forecast, the peak of the energy demand would start falling around 2030. The energy efficiency improvement would reduce energy demand after 2030 on average by 8.4% until 2050 that eventually will decrease emission intensity in the BAU scenario level.

Based on the energy balance in the scope of the measures in

Wrocław under current trends and slight additional efforts by applying future-effective GHG emission factors, it may be sourced emission prediction scenario, mapped as "business as usual". According to the IPCC inventory practices, the implementation of the emission forecast requires appropriate applying emission factors based on extrapolation to past inventory periods covered by this scenario (IPCC, 2006). Factors that should be considered vary with the site-specific conditions in a previous inventory year (backcasting to the year 1990), types of technologies in the application or sector, changes in determined activity level and changes in the calculation procedures.

The fulfilled in this study forecast represents the maximum achievable CO₂ savings for the year 2050 without significant climate mitigation actions in the urban area. Fig. 5 shows how GHG emissions would be distributed over the range of emission sources from 2020 to 2050 in BAU scenario. Accordingly, an emissions budget for the city of Wrocław in the case of "no climate action" in 2030 is approximately 4929.1 thousand tons of CO₂-eq, which is equivalent to an increase of 13.3% compared to 2010 level. The total energy demand in 2050 would decrease by 7.7% compared to 2030 and emissions also decrease by 5.7% (283.5 kt of CO₂-eq) respectively. Electricity and heat demand compared to 2010 would rise rapidly until 2030, and after that would

decline influenced by basic efficiency saving measures and residents behavior changes. Emissions from residential sector would reduce after 2030 by 7.9% (137.8 kt of CO₂-eq) up to 2050. The GHG emission from transport in BAU scenario shows the significant reduction by 15.3% after 2030.

The analysis of current trends of CO₂ emissions and reduction potential in Wrocław municipality shows that Wrocław as one of the high dynamically developing Polish cities still has a high possibility for energy efficiency improvements. Realization of the city's low carbon strategy requires establishing climate change priorities, including plans for increasing energy efficiency and clean energy technologies, renewable energy strategy, long perspective transportation improvement programs and green buildings design.

Such changes at Wrocław urban area are possible, but full implementation of all the measures would face a lot of challenges in case of the rising energy demand caused by economic growth and increasing level of life. The major weaknesses in a CO₂ level reduction in the household sector are (Low Emission Economy Plan, 2015):

- the age structure of buildings within the municipality (old buildings are dominated);
- high cost of municipal buildings retrofitting and increasing the cost of energy supply;
- existing persistent level of buildings energy demand;
- the problem of low emissions, mainly from individual coal fueled heating systems;
- progressive suburbanization in the city;

in transportation:

- heavy traffic situation and low capacity of roads in the city;
- increase share of individual transport and a small part of trips by public transport;
- the age structure of transport (high amounts of used vehicles from EU);
- the efficiency of road vehicles (low prevalence of hybrid and electric vehicles);

industrial sector:

- the vicinity of the large industrial and power plants;
- high energy demand in industrial processes in a local industrial network;
- combined heat and power (CHP) plants are fueled mainly by black coal;
- the minor role of green power production and domestic renewable energy industry.

Wrocław municipality also has significant opportunities for decreasing urban GHG emissions due to implementation of new house construction standards; increasing the energy efficiency of residential and commercial buildings; modernization and applying of progressive energy-saving technologies, declining the consumption of conventional energy sources; changes in transportation modes and efficiency of vehicles; improving waste management, stimulating environmental awareness; using perspectives from EU to support investment in renewable energy. Furthermore, in the household sector, overall efficiency will increase in a result of stricter standards for new constructions (passive house techniques) and retrofit of old building stock, fuel switching from solid fuels to oil and gas in private heating systems. Goals in the industrial sector achieve by long term focus on efficiency savings and renewable energy generation. The new possible directions of redeveloping in road system: an intelligent transport system, traffic-situation models (Costabile and Allegrini, 2008; Smit et al., 2010); reducing traffic on streets and amount of transport crossing a city should be supported.

The numerous of measures defined above in Wrocław have been started in the past 15 years and would increase significantly in future. In combination with matching conditions at state and local level the many ideas are running as follows: the new Environmental Protection Program (The Municipal Office of Wrocław, 2016); plans for modernization and development of district heating network, includes modernization of coal fueled heating systems in settlements, known as 'Kawka Project' (Environment Wrocław Portal; Low Emission Economy Plan, 2015), plans for rebuilding urban transportation system and promoting alternative means of communication (walking and cycling promoting), the involvement of social and NGOs in promoting energy efficiency, also project of renewable energy for offices of authority in Wrocław (PortalKomunalny.pl) and experimental solutions for urban greenery (in the framework of Horizon 2020 Projects) (PortalKomunalny.pl). In the legislative background it includes Polish legislation on management of emissions of GHG (Poland Ministry of Environment, 2009) and energy efficiency standards; energy efficiency EU packages and renewable energy requirements (European Commission, 2011a, 2011b, 2013).

Implementation of GHG mitigation measures at Wrocław urban area is critical towards achieving progress in emission reduction targets. The analysis indicates that the reduction of coal consumption is the primary task for the improving the energy efficiency and reduction of carbon emissions. Decreasing coal use in Wrocław has provided a drop of CO₂ emissions from energy sources nearly by 43% in 2013 compared to 1990 base year. The work towards advancing clean technologies and efficiency increment has influenced the largest emission reductions in industrial processes (fell down by 61% between 1990 and 2013). A modernization and construction of heating infrastructure and initiatives to replace other appliances causing high GHG significantly reduced heating consumption and relative emissions in the sector (over 41% up to 2013). The largest emission reductions from 1990 through 2013 occurred in waste management sector (by 97%–581 Mg CO₂-eq) as result of treating the methane gas from landfills (Low Emission Economy Plan, 2015). Increasing a share of renewable carriers (including biomass) in energy supply system in Wrocław about 15% until 2020 (5 GWh/year) leads to a reduction of carbon emissions by 645 kt CO₂-eq per year (Low Emission Economy Plan, 2015).

5. Conclusion

The world's cities experience shows that there are many challenges for municipalities, however, cities also offer opportunities for sustainable development and innovation addressing to the actions on direct impact on the health and environmental stability, including climate change adaptation and mitigation strategies, as well as by promoting energy efficiency and smart mobility network, increasing citizen's environmental awareness. The information on urban GHG emissions at the local level, their sources and framework should help to control and manage emissions, to create strategies to minimize them. The city-scale GHG accounting techniques are more compatible with the urban infrastructure-based energy supply chain and related GHG emissions footprint and measure the success of local climate action. Local emission accounts provide mitigation and adaptation measures, which would be implemented across sectors in certain communities regarding both climate and non-climate drivers.

Finally, the study discusses these results and gives recommendations for quantifying urban greenhouse gas emissions and establishes goals for emissions reductions at Wrocław urban area. In the city dimension, the results reported by Baseline Emission Inventory (BEI) in Wrocław Low Emission Economy Plan, indicate that over 85% of total GHG emissions in Wrocław municipality in 2013 (4113.77 kilotons CO₂-eq) are resulting from energy consumption. Settlements (energy use in buildings) are responsible for 63% of citywide GHG emissions through the consumption of electricity, heating and district heating, using coal and natural gas in individual heating systems. Energy use in the

transportation sector contributes an additional 24%. Industrial processes (result of manufacturing processing of raw materials) share is near 12%. The remaining emissions are from waste management and AFOLU sector Agriculture, Forestry and Other Land Use.

The given Wrocław's GHG achievements are significant and the potential for energy efficiency in the municipality is still high. The main challenges are if increased energy efficiency will outweigh the effect of growing demand for energy and resources caused by economic growth and increasing level of life. The provided at this work “business as usual” scenario looked at the future level of CO₂ reduction, which could be achieved by Wrocław Municipality in case non-significant efforts in climate adaptation and mitigation. A scenario is not a single static prediction of the future, but rather logical vision how the situation will unfold. It gives an opportunity for rehearsing the future events or outcomes of reducing these energy emissions.

Implementation of action plans and guarantees to reducing GHG emission in the city requires a careful understanding of the characteristics of urban resident's lifestyle and consumption. The results of reflecting total GHG emissions from urban consumption in Wrocław are presented in the form of the interactive Sankey diagram. This Sankey diagram from 2013 specifies how much of that energy demand in consuming sectors e.g. energy use in buildings, transportation, industrial processes, AFOLU, waste and waste water treatment sector is provided by coal, natural gas, petroleum, electricity and renewable energy resources. The energy flows converted by related emission factors are coming down to the current trends in greenhouse gas emissions in Wrocław. The provided analysis could form the basis for a new energy structure for different municipal GHG sources through increasing energy efficiency and development of renewable energy technologies in Wrocław.

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