Using Life Cycle Assessment to inform Municipal Climate Mitigation Planning

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Abstract

Local governments can play a key role in reducing emissions associated with local energy use. 17 Polish municipalities provided data on energy use and CO_2 emissions for 2015. Life Cycle Assessment (LCA) was used to calculate lifecycle impact indicators for greenhouse gases, particulate matter, acidification and eutrophication associated with the annual energy demand in each municipality. Results showed that impacts from energy use increase almost proportionally with total energy used in the participating municipalities due to the heavy reliance on fossil fuels. Analysis of two municipalities of similar size showed that impacts can be attributed to different usage sectors. For one municipality, energy plans should focus on reducing emissions from private transport and associated fuel use. For the other, energy plans should focus on reducing energy demand from residential buildings. This means that a 'one-size-fits-all' energy plan, which may be developed at a national level, would not fit

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all municipalities. The application of LCA allows for identifying and informing energy planning with impact reduction potential for multiple environmental pressures. Analysis of the provided energy use and CO_2 data showed large uncertainties in CO_2 emission intensities and allowing for sufficient time and guidance in the energy and emissions accounting is recommended.

Keywords: Municipal energy use, life cycle assessment, climate change mitigation, municipal planning

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1. Introduction

The last decades have seen a push towards a global low-carbon society. Within Europe, the European Commission is driving the transition, having set challenging mandatory targets for Member States that require significant changes in energy use. This includes the EU 2020 climate and energy package, specifying a 20 % greenhouse gas (GHG) emission reduction with respect to the 1990 baseline, 20 % of EU energy produced from renewable sources, and a 20 % improvement in energy efficiency [1, 2] and the 2030 climate and energy framework, which extends these targets to at least 40%, 27% and 27%, respectively [3, 4].

To face these challenges, coordinated energy planning is required at international and national levels, as well as regional and local levels. Local governments are particularly well placed to support the transition since cities and urban areas contain the highest population densities, consume the most energy and produce the most CO_2 emissions globally [5]. Local-level planning is important to develop renewable energy sources which have an intrinsic site-specific nature, but in addition local governments can encourage lower energy consumption as regulators, assist in identifying relevant energy-saving measures and technologies and increase citizen environmental awareness [6-8].

Across Europe, urban areas are directly targeted by several of the European Regional Development Fund investment priorities, and one of the main ways to streamline municipal energy planning (and to implement the EU 2030 objectives at local level) is the Covenant of Mayors (CoM) for Climate & Energy [5]. Participating cities to the CoM, referred to as signatories, commit to document their efforts to reduce GHG emissions in a Sustainable Energy and Climate Action Plan (SECAP). Developing low-carbon energy plans requires analysis of energy demand and supply to understand the criticalities of energy in the region, and the plan should include a Baseline Emission Inventory (BEI). In this way, the production of an energy baseline is the first step in energy planning. Subsequent steps include an assessment of actions to reduce primary energy consumption and increase the energy production from renewable energy sources, as well as addressing any challenges found by the energy baseline.

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Resource mapping is conducted to determine how much energy is available from local sources [9]. Focusing on key use sectors may highlight where regional government intervention can be most effective.

The literature contains many examples of municipal energy analysis and planning ranging from case studies focusing on the energy planning aspects and strategies [10, 11] to model-based scenario development using the energy-economic (MARKAL-)TIMES model [7, 12]. While the focus of these studies is not on the accounting of the energy production and use of the municipality, they require an understanding of the baseline energy use and emissions inventory to develop planning, strategies, and scenarios effectively. Energy balances for multiple municipalities in north Greece are for example presented in [13] and greenhouse gas emissions for a single Portuguese municipality are discussed in [14]. As the number of signatories to the CoM increases, baseline emission inventories become more readily available allowing for cross-municipal analysis, see for example [13, 15-18].

A key indicator used for monitoring performance is CO_2 emissions (absolute and per capita), which can be divided by direct and indirect emissions [19]. Other indicators are for example related to the consumption of various energy carriers, generation of energy from local renewable sources and use of electricity from renewable sources. Direct CO_2 emissions are emitted directly within the cities primarily from combustion processes, whilst indirect CO_2 emissions are usually related to the production of electricity or heat and relate to the implication of a municipal energy system on the national energy system [19, 20]. Although these indirect emissions are often located outside of the city boundary, including them is important to obtain a more accurate reflection of a cities' carbon footprint [20, 21]. A primary way to assess the different types of emissions and their resulting impacts is by applying Life Cycle Assessment (LCA), a tool used to assess environmental impacts of a technological system by accounting for all emissions along the full value chain and over the full life cycle. Few studies present the energy use and emissions from a municipality in a life cycle perspective, even though the reporting of the baseline emissions inventory in the CoM allows for the use of life cycle assessment (LCA) to report emissions factors [22]. One recent article found that the energy associated greenhouse gas emissions using LCA lead to approximately 20% higher GHG emissions for a municipality in Italy, which could have significant influence on the identification of climate strategies. More generally, the authors conclude that the LCA methodology can be more effective in reducing global greenhouse gas emissions levels due to its inclusive systemic accounting procedure [23].

One aspect of using LCA in the context of analysing the energy use in municipalities is not touched upon in the above-cited literature. LCA allows for assessing potential environmental impacts across a number of impact categories other than greenhouse gas emissions, such as acidification potential, particulate matter emissions, and eutrophication potential. Thus, a life cycle approach to analysing energy use in municipalities can potentially aid in developing energy plans that ensure reduction of environmental impacts on multiple fronts.

This article presents an analysis of the energy use and life cycle environmental impacts of 17 municipalities in Poland participating in a research project on energy self-sufficiency [24]. The objective is to provide a baseline with an outlook to ultimately improving energy security and environmental quality and developing low-carbon energy plans. Per municipality, data sheets were prepared regarding energy use for the year 2015, categorized according to the type of energy used and the sector it was used within. The data were used to quantify energy use, and assess key emission and impact indicators using LCA. In addition to presenting overall analysis of the 17 municipalities, selected results of the energy and emissions analysis from two example municipalities are shown and used as an example to discuss the production of future energy plans. In addition, the article discusses the inherent data uncertainties present in this type of analysis, and how they may be minimized by streamlining the data collection process. The novelty of this work is that multiple municipalities are studied rather than an isolated case from a life cycle perspective. Energy use in the municipality is coupled directly to LCA modelling, allowing for the calculation of multiple impact indicators.

An overview of the data collection process and analysis method is presented in section 2. Subsequently, a results summary for energy use for all 17 municipalities in the study is given in section 3.1. A comparative analysis detailing the environmental impacts for two municipalities is presented in section 3.2. This is followed by a discussion of data uncertainties and recommendations in sections 4.1 and 4.2, respectively, and policy implications (and conclusions) in section 5.

2. Methods

The municipal energy mix was first quantified in 17 Polish municipalities for the year 2015. While none of these municipalities is a signatory to the CoM, a similar approach to energy use reporting was taken as in the reporting for the Covenant of Mayors [25]. Energy use was categorized by the usage sectors transport (private and public), buildings (several sub-categories) and industry. Energy carriers were classified according to pre-produced energy carriers available to municipal end-users. Examples are electrical energy, heat/cold from district heating, fossil fuels, and various (local) renewable energy sources. Data on annual energy use and CO_2 emissions was collected from the municipalities by sending out a data collection template, to be filled out by selected compilers at the participating municipalities. An overview of the data collection template is given in Table 1. Note that the data template differs slightly from the CoM template [25]. On the usage sectors, tertiary buildings are referred to as non-municipal buildings, the municipal fleet is included as private transport, and emissions from agriculture, forestry and fisheries are included under industry. On the energy carrier side, wind and photovoltaic energy were added to the data template and some sectors were relabelled (e.g gasoline to petrol).

Over the course of three months the 17 municipalities returned their data sheets. These were subsequently reviewed for quality assurance and data was updated where necessary.

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Table 1: Data input template for annual energy use or CO_2 emissions, after [25].

	Electricity	Heat/cold	Natural gas	Liquid gas	Heating oil	Diesel	Petrol	Lignite	Hard coal	Other fossil	Vegetable oil and bio-waste	Biofuel	Wood and other biomass	Solar heating	Photovoltaics	Wind	Geothermal
Buildings (municipal)																	
Buildings (non-municipal)																	
Buildings (residential)																	
Industry																	
Public lighting																	
Private transport																	
Public transport																	

To determine the life cycle emissions and impacts of energy use in the municipality, both the production of energy carriers and the actual use of these energy carrier products were considered using LCA. An LCA can be divided into three phases as outlined in the international standard ISO 14040:2006 [26]. First, system boundaries and a functional unit of analysis need to be defined. Second, a Life Cycle Inventory (LCI) model is constructed that accounts for all inputs (resource use) and outputs (emissions and waste) required to fulfil demand for the functional unit. An LCI results in a quantification of the life cycle emissions from single pollutants (e.g. CO_2). The third phase of LCA, impact assessment, groups these single pollutant emissions into meaningful impact categories by using impact indicators, such as global warming potential (in kg CO_2-eq) or terrestrial acidification potential (in kg SO_2-eq). Parallel to these three phases, there is ongoing interpretation to allow for an iterative modelling procedure [26].

System boundaries for the study are shown in Figure 1, and include the production, distribution and use of energy carriers and fuels. As functional unit of analysis, 1 GJ of gross energy 'imported' in the municipality was chosen. Gross energy imports were chosen over net energy usage because it is a common defining denominator for all energy flows into the municipality and therefore a convenient unit of analysis.

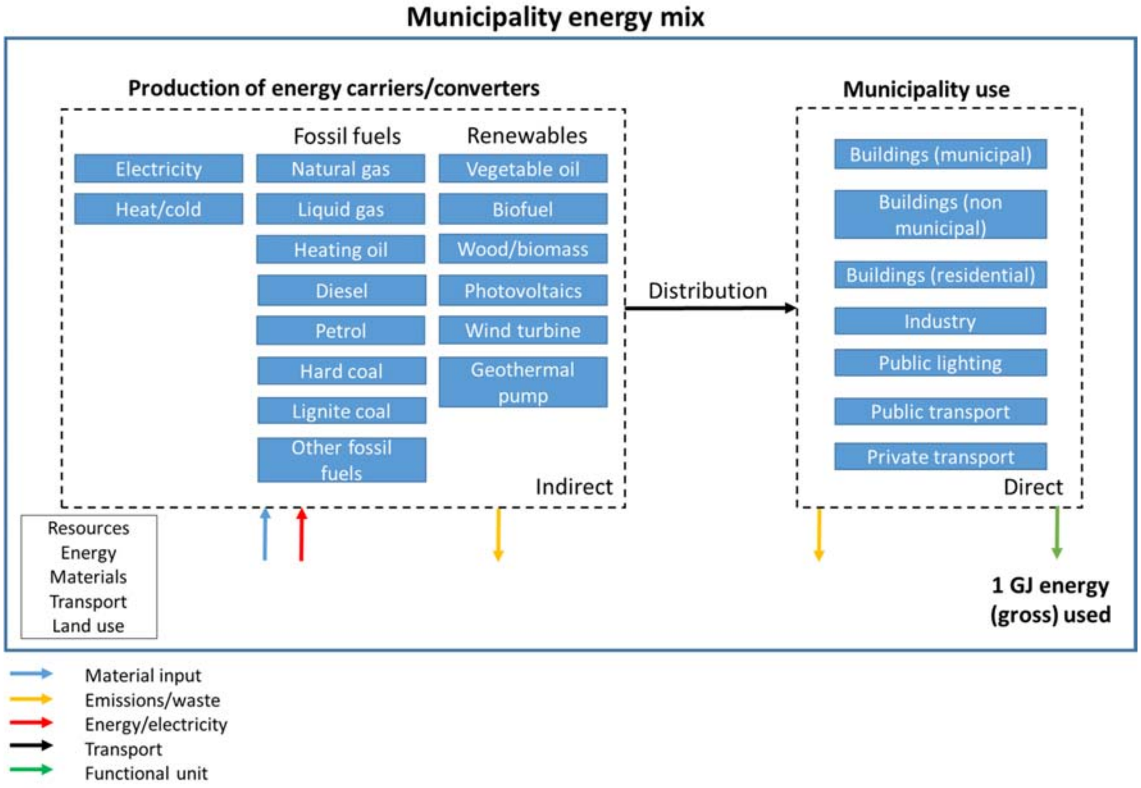

Figure 1. System boundaries used in the Life Cycle Assessment (LCA).

The Life Cycle Inventory model consisted of a combination of the primary data sourced from the municipality, secondary emission inventory data from public inventory reports, and secondary data from a life cycle inventory database. Energy use data were collected directly from the municipalities, broken down by energy carrier and application. In addition to the energy data, each municipality also provided data on direct CO_2 emissions related to use of energy, allowing local CO_2 emission factors to be calculated for each energy carrier type. Where not available for single municipalities, CO_2 emission factors averaged across all municipalities who submitted data in the project were used. The model was supplemented with non-CO_2 emissions using emission factors from the Polish national inventory report on GHG [27] and criteria air pollutants [28], as well as the EMEP/EEA air pollutant emission inventory guidebook [29]. Data with respect to the production of the energy carriers were taken from the life cycle inventory database Ecoinvent v3.1 [30].

All modelling was performed using the dedicated LCA software package Simapro, Analyst version 8.1.1.16 [31]. Impact results are presented for four categories available using the ReCiPe impact assessment method [32]. These impact categories and their corresponding impact indicators include climate change (GWP_{100} in kg CO_2-eq), particulate matter formation (PMFP in PM_{10}-eq), terrestrial acidification (AP in kg SO_2-eq) and freshwater eutrophication (EP in kg P-eq).

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3. Results

Energy use across the 17 investigated municipalities for the year 2015 is presented in section 3.1. These results both summarise the data (as collected direct from the municipalities) and present further indicator analysis. For more detail, comparison life cycle impact assessment results for two selected municipalities of similar size are subsequently discussed in section 3.2.

3.1 Energy use in the municipalities

A breakdown of municipality energy use by sector and energy carrier is shown in Figure 2 for the year 2015. The full range between minimum and maximum reported numbers is shown, as well as the median and 1st and 3rd quartile of the dataset. Out of 17 investigated municipalities, most municipalities used electrical energy and various fossil fuels including hard coal and lignite, diesel, petrol and natural gas for use in buildings (principally residential) and for private transport. In addition, the boxplots indicate considerable variation in reported energy usage and energy carrier values. For example, one municipality classified all its energy usage as non-municipal.

In Figure 3 the residential and total energy use are plotted against municipal population size. As can be expected, both residential and total energy use increased with population size. Residential energy use and population size are stronger correlated than the total energy use and population size. This is since some types of energy sector use, such as industrial use, do not necessarily scale well with population size, but are determined by industry location. The median value in the dataset for residential energy use per capita was around 20 GJ per year, whilst the media value for total energy use per capita was around 60 GJ per year. No clear correlations were found between municipal population size and a specific energy carrier, though the direct combustion of fossil fuels appears to decrease with population size in favour of energy carriers such as heat from district heating or electricity from the grid.

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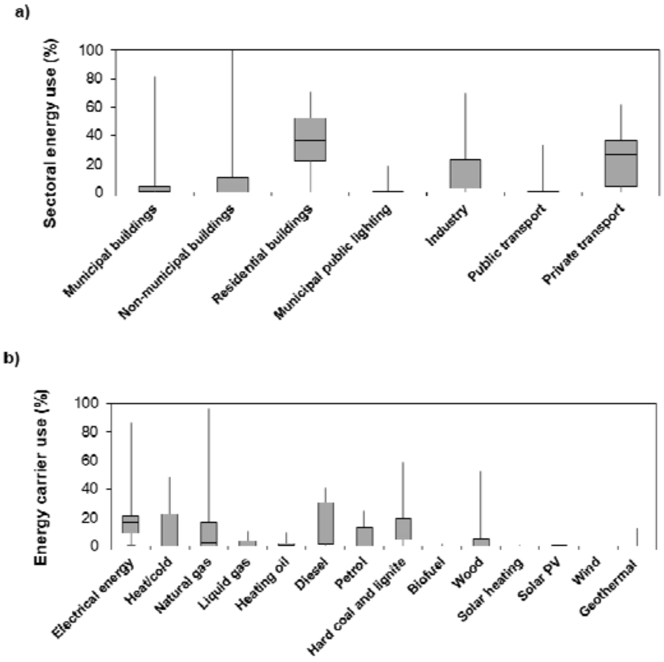

Figure 2. Box plots showing the distribution of the contribution (%) of a) energy use sector and b) energy carriers towards total municipal energy use, for the year 2015. Data reported in data template described in Table 1 by municipalities participating in the research.

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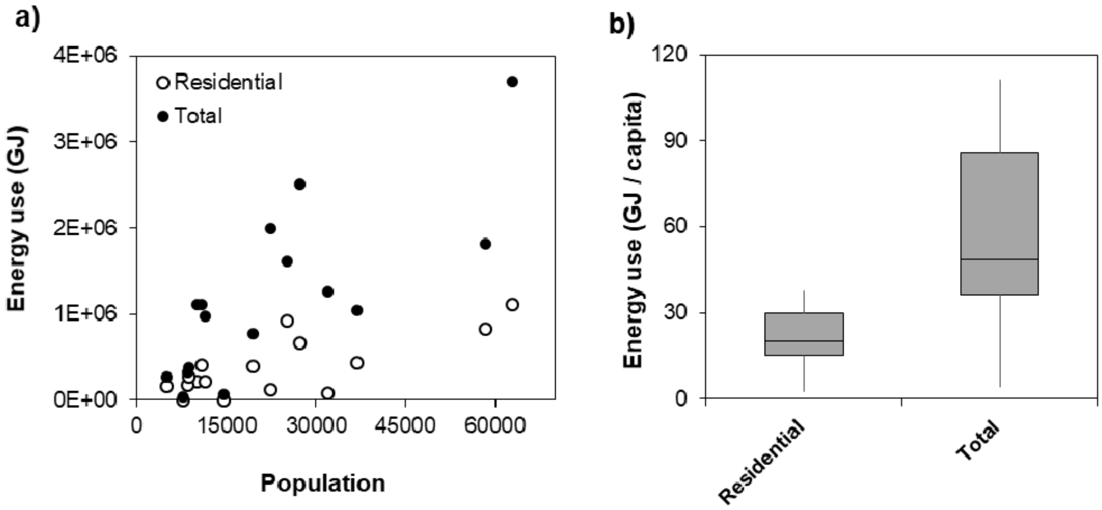

Figure 3. Residential and total municipal energy use (GJ) with varying population size for the year 2015, expressed in terms of a) total values and b) per capita. One outlier is removed from these plots. Data reported in data template described in Table 1 by municipalities participating in the research.

Figure 4 shows the relationship of selected impact indicators with total municipal energy use. In general, impacts from energy use increase almost linearly with total energy used. One explanation is that, ultimately, for the municipalities in this study most energy (including the imported electricity and district heating) is produced from the combustion of fossil fuels and wood. One municipality, with an annual energy use of approximately 2 PJ, has significantly higher lifecycle impacts for the indicators global warming potential, particulate matter formation potential, and terrestrial acidification potential. This municipality has a significant (coal and lignite fired) electricity consuming industry. The municipality with the highest eutrophication potential (and an annual energy use of 1.26 PJ) has a significant amount of coal combustion in residential buildings compared to the other municipalities. Through the life cycle database ecoinvent, the main cause for eutrophication can traced to the treatment of spoil from coal and lignite mining. As a result, the municipalities that are either directly or indirectly (by using electricity from coal and lignite) reliant on coal or lignite will therefore have high eutrophication indicator scores.

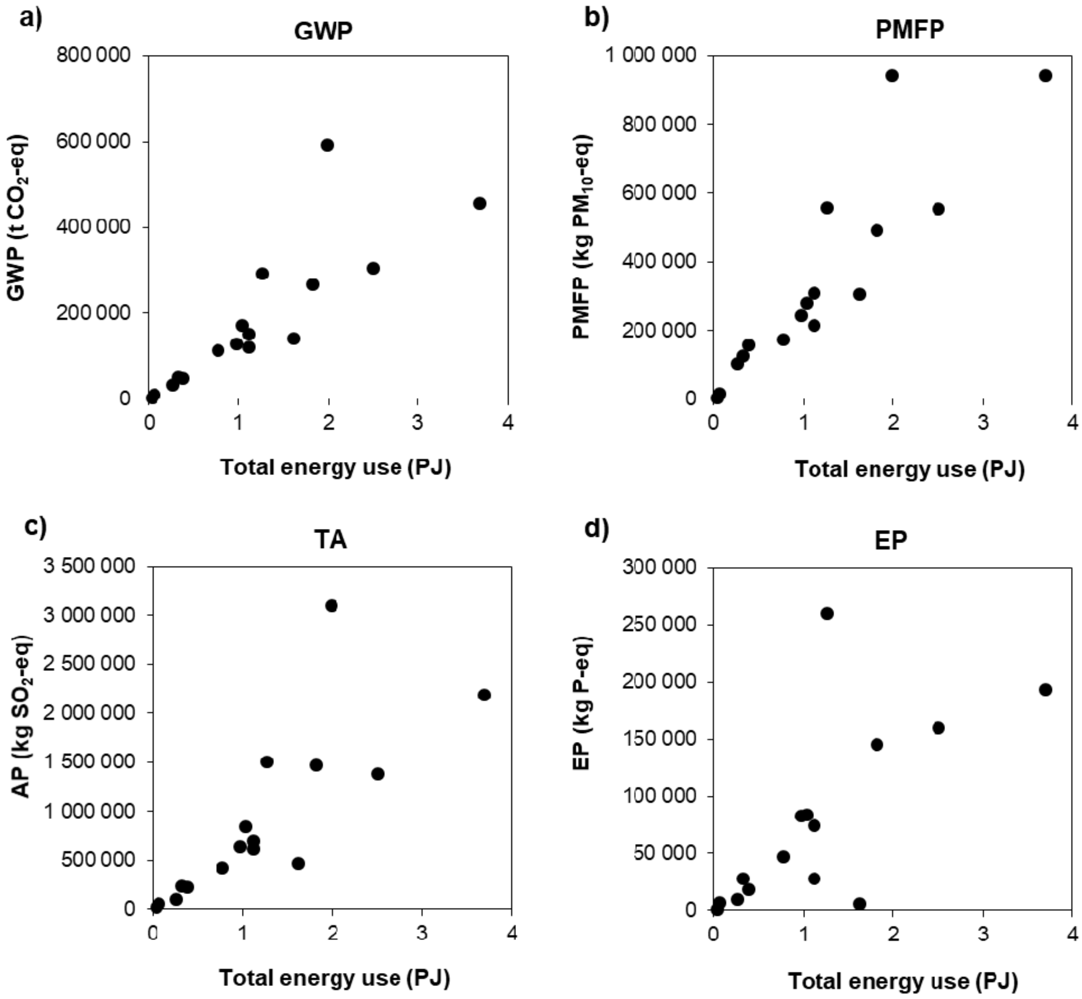

Figure 4. Life Cycle Assessment results. Relationship of a) GWP (global warming potential), b) PMFP (particulate matter formation potential), c) AP (terrestrial acidification potential), and d) EP (freshwater eutrophication potential) with total energy use in the municipality for the year 2015. One outlier is removed from these plots.

3.2 Comparative analysis for two municipalities

In order to exemplify differences between municipalities, two similarly sized municipalities are directly compared and discussed in this section. Both municipalities reported similar total annual energy use (1.1 PJ) and a similar number of inhabitants (around 10 500) in the year 2015, and are designated here Municipality 1 and 2.

Figure 5 shows a breakdown of the energy demand for the year 2015 by energy use sector and the contribution of each of the energy carriers, for the selected municipalities. For Municipality 1, the largest energy use sector was private transport, whilst for Municipality 2, the largest energy use sector was residential buildings. The type of energy usage is reflected by use of different energy carriers. Most of private transport is fuelled by diesel and part of the residential buildings in Municipality 2 are connected to district heating (expressed as heat/cold in Figure 5) for their heating energy needs. Other energy carriers used for residential energy needs in Municipality 2 are electricity and natural gas. In Municipality 1 combustion of coal in domestic furnaces is the main source of energy.

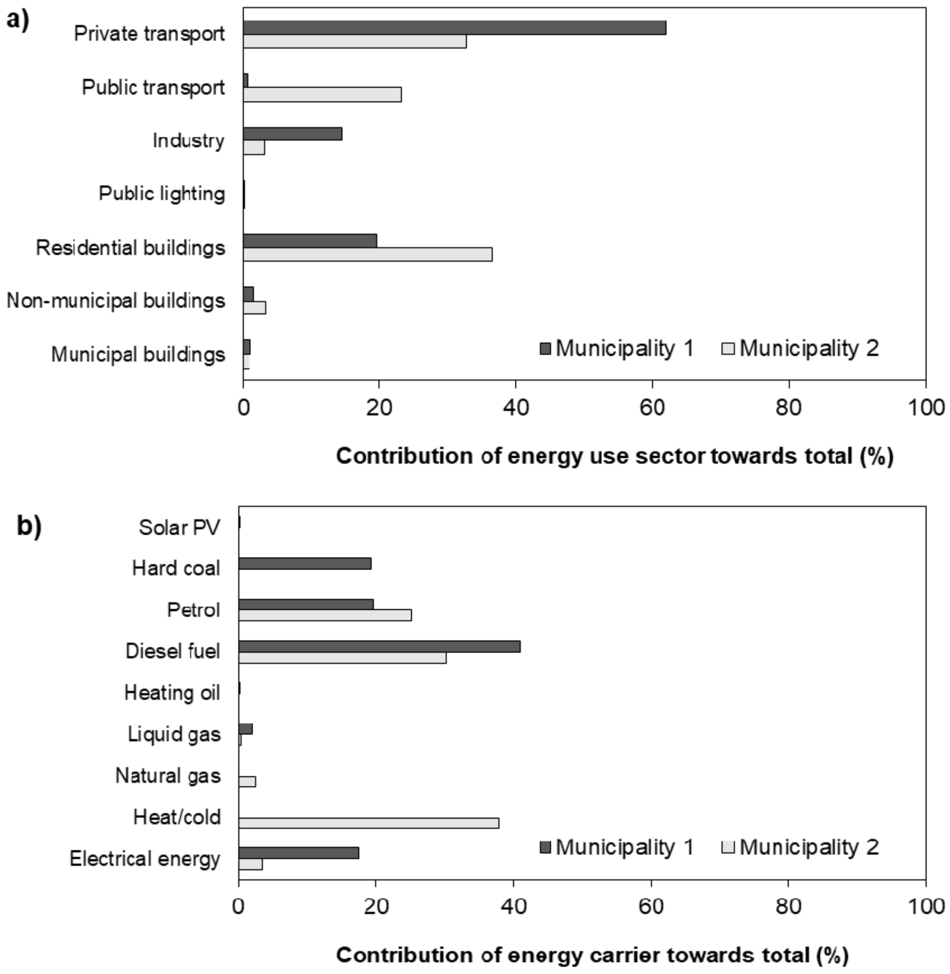

Figure 5: Comparative energy use overview for two selected municipalities for the year 2015, showing the contribution of a) each energy use sector, and b) each energy carrier, towards total energy use. Data provided by the municipalities in the data template described in Table 1.

Impact assessment results of the LCA model for the two municipalities are shown in Figure 6. Municipality 2 had slightly lower impacts across all categories than Municipality 1. Since the municipalities had similar total energy use and capita, impacts were also similar when expressed per unit energy or per capita.

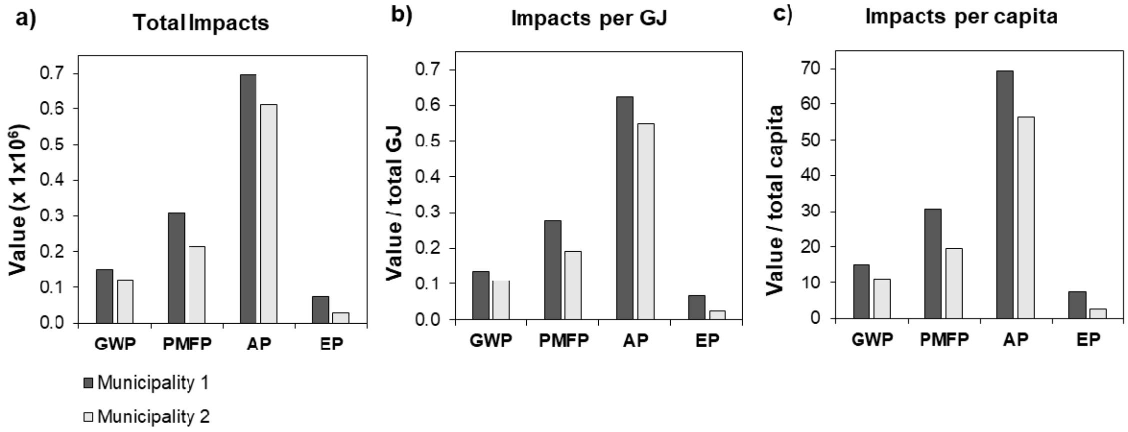

Figure 6: Selected impact indicators for the municipalities for the year 2015, including GWP (global warming potential with unit of t CO_2-eq), PMFP (particulate matter formation potential with unit of kg PM_{10}-eq), AP (terrestrial acidification potential with unit of kg SO_2-eq) and EP (freshwater eutrophication potential with unit of kg P-eq). a) Total impacts, b) Impacts per GJ and c) Impacts per capita.

One way to easily visualize the contribution of individual energy use categories and sources of environmental impacts is through use of Sankey diagrams [33]. The Sankey diagram gives a feel of the magnitude of singular flows, which is of key relevance for developing a municipal future energy-use or low emissions plan. Figure 7 shows a Sankey diagram where GHG emissions (in kg CO_2-eq per GJ energy used) for the year 2015 are broken down by use sector and contributing process for the municipalities. In addition, the flows are also split into direct and indirect categories. Direct environmental impacts are those impacts resulting from direct emissions in the municipality, e.g. diesel combustion for transport. Indirect emissions occur along the value chain, for example, in the production of electricity. Only processes contributing more than 5% to total impacts are shown, as these processes are the key 'hotspots' where impacts may be reduced. The remaining contributing processes are labelled as other direct or indirect contributions. As a result, the district heating is singled out in Figure 7b as a source of emissions for building energy use in Municipality 2, but not electricity or natural gas combustion as these contribute less than 5% and are included in other indirect and other direct contributions, respectively.

For Municipality 1, most climate change impacts can be attributed to private transport, and associated diesel/petrol combustion, as well as electricity (produced from combined lignite and hard coal). This reflects the energy demand shown in Figure 5, although there is a higher contribution from electricity towards GHG emissions than would be expected at first glance from the percentage in the figure. The reason for this is the electricity data represent use of electricity in the municipality that is available on the Polish grid (i.e. imported into the municipality). The life cycle emissions of this electricity are relatively high as production of the electricity comes at a conversion cost dependent on power plant efficiency. In contrast, fossil fuel use data represent the gross energy available in the fuel, and therefore emissions per GJ energy embodied in coal or GJ energy embodied in diesel are lower than per GJ electricity.

For Municipality 2, most climate change impacts derive from emissions from residential buildings, and associated use of district heating. This again reflects the energy demand shown in Figure 5. A higher proportion of impacts derive from indirect emissions from production of the fuels and energy carriers than direct emissions relating to the energy carrier use. This reflects the fact that CO_2 emissions are not directly given off during use of district heating, but rather, during production of the heat, which for the purposes of this article is considered external to the municipality and therefore labelled as an indirect emission.

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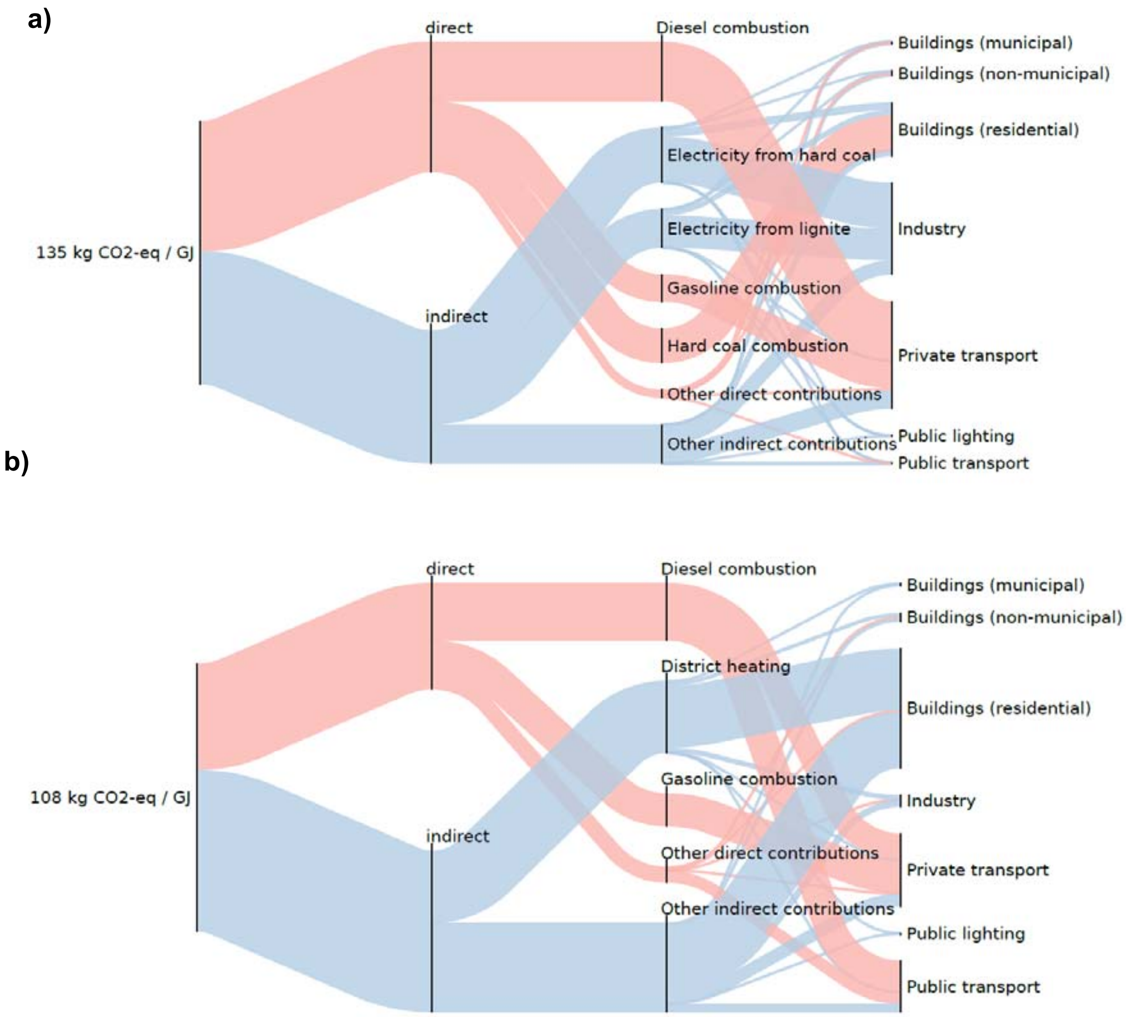

Figure 7: Breakdown of global warming potential (kg CO_2-eq) per GJ energy used in a) Municipality 1, and b) Municipality 2, for the year 2015, by use sector and process. Direct emissions are depicted in red, indirect emissions are depicted in blue.

4. Discussion

4.1 Data uncertainties

Quantifying municipal energy use and calculating associated emissions and life cycle impacts is inherently reliant upon the quality of the input data collected. Since the data used are collected from a large variety of different sources (and from a wide variety of contact persons), understanding and minimizing data uncertainties are key.

Analysis of the distribution in the received data is therefore of interest. Due to the nature of variation in energy use in different regions, it is difficult to investigate the uncertainties associated in the energy use data given with no further data available for comparison. However, municipalities also supplied data on annual CO_2 emissions resulting from use of energy. Combined with the annual energy use data the resulting CO_2 emission factors (kg / GJ) are analysed here to indicate variation of the received data. Some local variation is expected in CO_2 emission factors due to changes in fuel quality and combustion technology. However, since CO_2 emissions from fuel combustion are closely linked to the fuel carbon content, a degree of continuity can be expected across the data collected from different municipalities.

Figure 8 shows the distribution of the CO_2 emission factors for different fuels. For convenience, all use sectors are grouped together. In Figure 8 the box depicts 1st quartile, median and 3rd quartile of the collected data. The whiskers indicate minimum and maximum of the collected values. Note that for hard coal, natural gas, liquid gas and heating oil, for clarity either minimum or maximum (or both minimum and maximum) lie outside the plotted range. To assist in presenting an overview of the distribution of data points, all individual points are plotted on top of the boxplot. Outliers were intentionally not removed as the figure represents the data as received from the municipalities.

From Figure 8 it can be seen that the calculated emission factors for some fuels (e.g. natural gas, petrol) were tightly grouped with a narrow interquartile range, but for other fuels (heating oil, hard coal), there was a wider interquartile range. In addition, some unusually high and low values were calculated from the reported data. In some instances, this was likely due to a straightforward unit conversion error. In other instances, an explanation could not be found, nor was provided by the municipalities upon request. In the LCA performed for this article local CO_2 emission factors were used where possible. However, in the case of outliers the municipal data were replaced with emission factors averaged across all other municipalities who submitted data in the project.

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For some fuels there was also variation in CO_2 emission factor between sectors. For example, values for hard coal combustion in residential buildings varied from 58 to 107 kg CO_2 / GJ, whereas variation for industry was much smaller (between 88 and 98 kg CO_2 / GJ). This may reflect variation in local combustion technology and fuel characteristics, but values on the lower end are too low coal combustion. For example, the carbon content of various types of coal varies between 25.8 and 26.8 kg C / GJ [34]. Assuming complete combustion this would result in 94.6 kg CO_2 / GJ for the lower value. The deviation here likely points towards errors in accounting for CO_2 emissions and fuel demand. Alternatively, a significant part of the coal remains non-combusted.

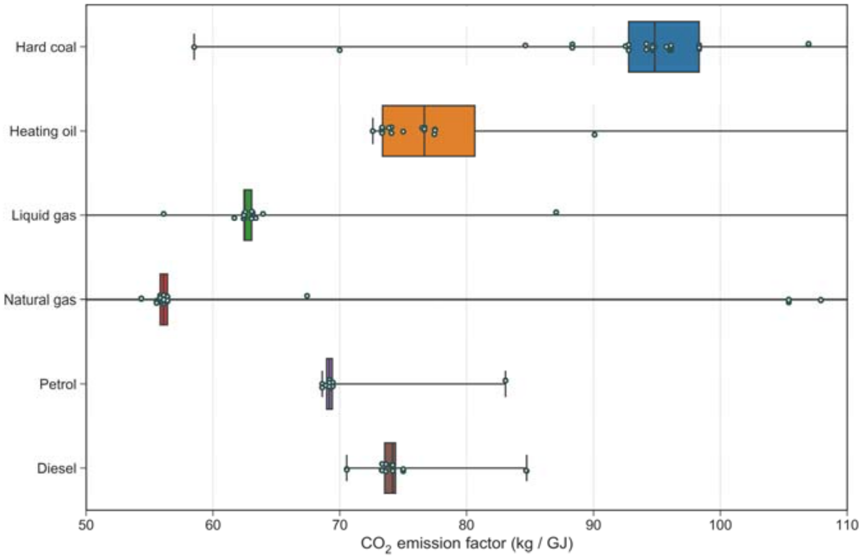

Figure 8. Box plots showing the distribution of stationary combustion CO_2 emission factors (kg/GJ) calculated from municipal data, for the year 2015. Outliers not shown on the figure include the following: 171 kg/GJ, 510 kg/GJ, 928 kg/GJ (hard coal), 124 kg/GJ, 127 kg/GJ, 231 kg/GJ, 278 kg/GJ, 742 kg/GJ and 873 kg/GJ (heating oil), 15 kg/GJ, 28 kg/GJ and 121 kg/GJ (liquid gas) and 0.02 kg/GJ, 151 kg/GJ (natural gas).

4.2 Recommendations for future research

The present study included a limited number of 17 participating municipalities, allowing for a manual and flexible approach to data collection and analysis, with sufficient time for feedback and dialogue with municipal partners. However, in larger studies the amount of data becomes too large to handle manually. Poland, for example, contains over 2400 municipalities, which poses a challenge for a national study of all municipalities. Here, some recommendations for future research are discussed based on the experiences from the present study. First, it is apparent that the time for data collection needs to be sufficiently long to allow the collection, review and feedback, and amendments. A workshop can be used at the project kick-off to educate all data compilers involved in the work, as well as a verification workshop or round to ensure the final data quality used by compilers. Second, in terms of the data collection process itself, the data input form needs to be fully explained with all units and conversions given. Data input, for example through a web-portal, needs to have automated checks and balances, based on allowed ranges of input values. This minimizes the risk of conversion errors and under or overvaluing data. In particular, it should also be ensured that all energy use data is consistent.

It should be noted that the above recommendations pertain to projects that are carried out independent of activities for the Covenant of Mayors. Most of the challenges regarding data submission, automated checks and research quality assurance and control are already covered and implemented by the Covenant of Mayors. The Joint Research Centre has both a software check and ‘human for the mitigation part of the SECAP template [25] . Where possible, it is recommended to use data reported to the CoM and base future analyses, such as more detailed LCA models, on data that is available via the CoM.

5. Conclusions and Policy Implications

A necessary precondition for reducing GHG emissions for climate change mitigation is knowledge about the source and drivers of emissions. Since local governments are well placed to enable and accelerate the transition to a low-carbon society, local energy use analysis is increasingly emphasized. Based on municipal energy footprint analysis, local policies can subsequently be developed to lower emissions. Life Cycle Assessment (LCA) is one method that allows for the calculation and assessment of direct and indirect lifecycle emissions and impacts from energy use.

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In this article, the energy use of 17 Polish municipalities in the year 2015 was investigated. Most municipalities used electrical energy and various fossil fuels in their energy mix, with most energy used in residential buildings and private transport. Both residential and total energy use increased with population size. Some indications were present that municipalities with smaller populations use mainly coal and wood for energy needs compared to the municipalities with larger population, possibly reflecting variation in local energy infrastructure, such as the availability of district heating. A very low proportion of energy from renewable sources was present in the energy mix, at odds with current Polish national renewable energy targets.

Results showed that future energy plans should be developed at a local level based on local characteristics and the emissions hotspots that can be identified from an LCA baseline. For the selected municipalities analysed, LCA lifecycle impacts from energy use in the year 2015 increased almost proportionally with total energy used. This may be explained by the heavy reliance on fossil fuels. However, further analysis of two selected municipalities showed that these impacts can be attributed to different sectors, depending on the energy use characteristics of each municipality. In some municipalities, private transport and residential energy use were the main drivers of emissions, whereas other municipalities had a considerable industrial sector. This means that a ‘one-size-fits-all’ energy plan, such as that which may be developed at a national level, does not fit all municipalities.

Thus, different strategies should be adopted for developing low-carbon energy plans for each municipality, based on reducing emissions from the most relevant sectors and energy carriers. Essentially, there are three options available for climate change mitigation: i) reduce demand for energy, ii) improve the production of energy (carriers), e.g. for example by more efficient processes, and iii) switch the source of energy to a lower emission alternative. For ‘Municipality 1’ analysed in this study, energy-use plans should focus on reducing emissions from private transport and associated diesel and petrol use, as well as switching electricity from lignite and hard coal to renewable energy sources for all use categories. In contrast, for ‘Municipality 2’, energy-use plans should focus on

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reducing energy demand from residential buildings in addition to reducing energy needs for transport. Examples of policies to achieve these effects may include allowing only newer cars, which are more efficient, in the city centre, along with promoting public transport options. Municipal procurement, as well as permits for industry, may specify the purchase of electricity from renewable sources as a condition.

Future energy-use plans should also reflect the specific Polish energy targets as outlined by the Polish Ministry of Economy [35]. For the year 2020 this includes a 15 % share of renewable energy sources in the final Polish energy mix consumed, and a 10 % market share of biofuels in Polish transport fuels in 2020. For the year 2015, Municipalities 1 and 2 analysed here contained negligible amounts of renewable energy sources in the municipal energy mix, thus the increase of renewable energy use, either by purchasing electricity from renewable sources, or utilizing renewable energy sources locally, is of key importance in the development of their low-carbon energy plans.

Understanding the uncertainties of work based on data submitted from municipalities and other entities is of high importance when using the results further to develop local GHG mitigation policies. Here, primary data for the LCA model was provided by each of the participating municipalities in the study. Despite efforts to harmonize data collection, there was considerable variation in primary emissions data for energy combustion processes. Minimizing these uncertainties, streamlining the approach, and facilitating comparison between municipalities to provide a solid energy baseline for future energy plans is key. Sustainable Energy and Climate Action Plans according to the guidelines and submitted to the Covenant of Mayors already provide a streamlined framework with a quality control procedure. For projects outside the CoM simple approaches are recommended for follow-up work, such as including capacity building workshops for data compilers in the project timeline, utilizing automated data input, and allowing a long enough timeline for review and feedback of data, which may improve data collection and quality significantly.

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Contrary to the LCA emission factors for GHG emissions employed for the CoM, this article employs a full LCA model based on the life cycle inventory database ecoinvent. This allowed for the calculation of other environmental impact indicators than global warming potential. The application of LCA serves two main purposes. First, it provides an overview to municipalities about emissions occurring within their boundaries, as well as emissions occurring in processes beyond the municipalities boundaries that ultimately can be attributed to municipal energy demand. Second, LCA provides the opportunity for estimating and highlighting environmental co-benefits associated with greenhouse gas emissions reductions resulting from implementation of a sustainable energy and climate plan.

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