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Consequential Implications of Municipal Energy System on City Carbon Footprints

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Abstract: Climate change mitigation is an important goal for cities globally. Energy production contributes more than half of the global greenhouse gas emissions, and thus the mitigation potential of local municipal energy systems is important for cities to recognize. The purpose of the study is to analyze the role of local municipal energy systems in the consumption-based carbon footprint of a city resident. The research supplements the previous carbon footprint assessments of city residents with an energy system implication analysis. The study includes 20 of the largest cities in Finland. The main findings of the study are as follows: first, the municipal combined heat and power energy system contributes surprisingly little (on average 18%) to the direct carbon footprint of city residents, supporting some previous findings about a high degree of outsourcing of emissions in cities in developed countries. Second, when indirect emissions (i.e., the implication of a municipal energy system on the national energy system) are allocated to city residents, the significance of the local energy system increases substantially to 32%. Finally, without the benefits of local combined heat and power technology based electricity consumption, the carbon footprints would have increased by an additional 13% to 47% due to the emissions from compensatory electricity production. The results also show that the direct application of consumption-based carbon assessment would imply a relatively low significance for municipal energy solutions. However, with a broader understanding of energy system dynamics, the significance of municipal energy increases substantially. The results emphasize the importance of the consequential energy system implications, which is typically left out of the evaluations of consumption-based carbon footprints.

Keywords: climate change mitigation; carbon footprint assessment; life cycle assessment; energy systems

1. Introduction

The share of anthropogenic GHG emissions due to energy use is globally estimated to be around 55% in 2011 [1]. Furthermore, the energy consumption in cities is estimated to already account for over 70% of energy-related emissions [2], and ongoing urbanization is likely to increase this share. It is obvious that climate change mitigation targets cannot be met without significant reductions in the GHG emissions caused by cities.

Although energy systems contribute to the vast majority of global anthropogenic GHG emissions, and high mitigation expectations are put on the de-carbonization of energy systems in many countries and municipalities, the share of local and even national energy supply systems covers only part of the energy requirements of any municipality. Cities and nations are part of highly globalized ecosystems where commodities are supplied based on market mechanisms. This leads to a situation in which the GHG emissions caused by a city or a nation due to demand can deviate significantly from those occurring within its geographical area [3], even if all the locally needed energy was generated locally. Thus, a major share of the energy consumption of a certain resident is likely to fall outside the reach of local energy policies and personal energy choices. On a larger scale, the same applies to the energy requirements of cities and nations. In 2011, it has been estimated that close to 50% of energy and GHG emissions embodied in consumption in Finland are imported [4]. When looking at the regional or city level, the share is likely even higher [3,5].

Since stationary energy is the primary source of GHG emissions, it would be necessary to reduce its impact on the carbon footprint of citizens, but the global spread of overall energy use aggravates efficient mitigation policy design. Multiple consumption levels can be defined e.g., [6,7]. For stationary energy consumption of city residents four levels can be distinguished: (1) the building level; (2) the local district energy level; (3) the national electricity grid level; and (4) the global level. The resident has the most influence on the building-level energy system. Residents naturally influence their energy consumption, but they may also influence the selection of the heating system and sometimes the on-site electricity production. In apartment buildings, residents have less influence because most of the decisions are made by the housing company, or even further away as a part of municipal decision-making [8,9]. In the case of district heating networks, the local energy producer—and thus local-level (e.g., municipal-level) decision-making—especially affects emissions from heating energy. In addition, if the local energy producer generates electricity, it partially affects GHG emissions also caused by local businesses and home electricity use—or it affects the average grid emissions according to its share. This depends on whether the local utility is assumed to sell the electricity first to the grid or directly to the area it serves. (See [10] for a detailed discussion.) The national grid, falling under the scope of national energy policies, naturally has an impact on the carbon footprint of a consumer. However, in the globalized environment we live in, the mitigation possibilities (even through national energy policies) are limited. In the end, a major and increasing share of emissions caused by a consumer, from housing to the use of services and goods, is spread around the globe in production and delivery chains. This significantly limits the impact potential of local and national energy policies.

Consumption-based embodied energy and carbon footprint assessments offer a potential way to study the embodied GHG emissions and the impacts of changes in the energy systems that affect the footprints [11]. While consumption-based carbon footprinting with a spatial perspective is already a relatively established research field [12–20], the previous carbon footprint studies of city residents have not properly taken into account the systemic nature of energy production and consumption within the city; instead, they have applied fixed GHG intensities based on average energy production. This is partly due to the environmental input–output utilized in the studies, which has the important inherent limitation of describing the average production [21]. While Wolfram et al. [22] have applied carbon footprinting to studying the impact of various renewable production penetration scenarios in Australia, and [15] and [9] have discussed the issue of municipal energy production impacts and have presented simple analyses using municipal energy production with Finnish case municipalities, the topic warrants further research.

The commonly presented estimate of cities' 70% contribution to GHG emissions is often criticized, as it does not represent the emissions caused within the city boundaries [23]. The question is how emissions are allocated based on consumption or production, and it has been stated that the share of emissions can vary considerably [24]. Numerous studies [24–26] present the variation of emissions per capita within cities globally. When the GHG emissions are allocated based on consumption or production, the results show that the differences can be substantial. In Nordic cases, the cities often demonstrate their own willingness to carry out energy planning [27], although national energy policies have an important role as well, since cities with local energy plans typically follow national policies [28].Apart from the carbon and energy footprint studies, implications for an energy system that arise due to changes in parts of the energy system have been studied from the perspectives of energy consumption and energy production. Studies such as Siler-Evans et al. [29] and Farhat

& Ugursal [30] have suggested that increasing or decreasing electricity consumption at the system level leads to similar changes in marginal energy production. Thus, for example, decreasing energy consumption leads to relatively higher emission savings, as if average electricity production had decreased instead. This is because emissions from marginal production tend to be much higher than that from average production. Studies such as Holttinen & Tuhkanen [31], Siitonen et al. [32], Pehnt et al. [33] and McCarthy & Yang [34] have suggested that similar implications are present when single measures or production technologies are introduced into an electricity system. Such studies focus more on initial system implications rather than the temporal development of the implications' positive effectiveness. Studies such as Olkkonen & Syri [35] and Zivin et al. [36] have suggested that marginal electricity can be highly variable, both spatially and temporally. For example, Roux et al. [37] and Kopsakangas-Savolainen et al. [38] have suggested that even short-term temporal changes in emissions are changing the actual carbon emissions caused by a subject.

In brief, the GHG assessment of cities still understates the consequential implications of local energy systems at the national level. First, cities usually report their emissions based on regional production instead of consumption. Second, if the carbon footprint approach is applied, it normally only considers the direct impact of carbon mitigation actions, while the consequential system impacts are missing. The influence of the consequential system impact may be crucial, especially when the least favorable technology in the system is replaced by a new highly favorable technology.

The purpose of the study is to demonstrate how an understanding of the consequential implications due to energy system dynamics can change the relative significance of municipality energy production choices compared with the traditional consumption-based carbon footprint assessments. The study supplements the consumption-based carbon footprint assessment of city residents with an energy system implication analysis. In the following chapters, the study will show that the municipal energy system directly contributes relatively little to the city residents' carbon footprint, but it has a substantially greater contribution when the consequential implications are accounted for. The study includes the 20 largest cities in Finland, each of which has its own district heat network with separate heat production and/or CHP production utilities. Section 2 presents the research materials and methods, Section 3 presents the results, and Section 4 presents the discussion and conclusions.

2. Materials and Methods

2.1. Materials

The study has two primary data sources. The consumption-based carbon footprint assessment utilizes Statistics Finland's Household Budget Survey, the most commonly used type of expenditure data in consumption-based carbon footprint assessments. The municipal energy analysis employs the Finnish Energy Industries statistics for municipal energy production. Statistics Finland's Household Budget Survey 2012 includes detailed data on the expenditure of Finnish households in 2012. In this study, the 20 largest cities are selected and analyzed separately. The total sample size of the survey is around 3500 households, of which 1661 reside in the selected 20 largest cities (Table 1). The survey uses the international COICOP division (Classification of Individual Consumption According to Purpose) [39], which consists of over 500 consumption categories. In addition to the expenditure data, the survey includes socioeconomic and spatial variables, as well as information about the houses of the households. The building-related variables include building type (detached house, terrace house, apartment building), age, and heating system.

Table 1. Descriptive 2012 statistics of the studied 20 largest cities in Finland.

	Sample Size (Households)	Population 2012	Income (€/year per Capita)	Living Space (m^2 per Capita)	Emissions from Local Energy Production (CO_2 kg/MWh) Heat	Electricity	Share of Households with District Heating	Share of Households Living in Apartment Buildings
Helsinki	362	598,000	23,700	37	188	419	86%	86%
Espoo	146	254,000	25,500	41	273	660	69%	55%
Vantaa	116	216,000	22,700	39	255	585	59%	53%
Tampere	136	204,000	22,200	41	168	347	78%	72%
Turku	107	179,000	21,100	40	293	684	79%	69%
Oulu	89	144,000	17,100	40	201	519	68%	50%
Jyväskylä	84	132,000	17,300	39	224	531	68%	69%
Lahti	64	102,000	17,700	40	232	526	83%	79%
Kuopio	71	97,000	19,100	42	84	103	68%	62%
Kouvola	67	88,000	21,100	50	238	558	40%	39%
Pori	58	83,000	17,000	46	190	426	44%	37%
Joensuu	50	74,000	16,000	39	130	319	58%	38%
Lappeenranta	58	72,000	17,500	44	86	90	67%	44%
Hämeenlinna *	34	67,000	18,000	47	104	222	66%	50%
Rovaniemi *	41	60,000	20,800	48	259	452	65%	33%
Vaasa *	31	60,000	18,800	41	287	703	70%	62%
Seinäjoki *	36	59,000	18,100	38	296	516	46%	22%
Salo *	40	55,000	21,500	51	146	291	25%	29%
Kotka *	41	55,000	17,100	41	95	208	66%	56%
Kokkola *	30	47,000	17,100	43	262	586	62%	37%

The other data sources—city statistics from Statistics Finland and the Finnish Energy Industries—were utilized to describe the cities and to localize the energy production GHG intensities in the carbon footprint model (see Section 2.2). Table 1 presents the sample sizes and some descriptive statistics of the studied cities. It should be noted that according to the data provider, in the Household Budget Survey the sample size is suggested to be around 50 households or more in order to be statistically representative. Thus, cities with a sample size below 50 households are marked with an asterisk.

2.2. Reference Carbon Footprint Model and GHG Emissions of the Municipal Energy System

The reference carbon footprint model of the study is a hybrid life cycle assessment (LCA) model combining an environmentally extended input–output (EE IO) analysis and a traditional process LCA, the same as utilized in Ottelin et al. [20] and Ala-Mantila et al. [40], and similar to those commonly used in consumption-based carbon footprint studies in general. (See the general assessment approach descriptions by Baynes and Wiedmann [11].) Generally, EE IO models are based on input–output economics [41]. The input–output tables of economies consist of monetary transaction matrices describing the monetary flows in the economy. In the environmental extension, environmental indicators are added to the matrices to follow the flow of emissions or material requirements. The input–output analysis is consistent with the idea of LCA—all the emissions released during the product or service life cycle (from cradle to gate) are included. While EE IO models are comprehensive, they lack accuracy. The aggregation of economic sectors causes aggregation error, and in addition, the assumptions of linearity and homogeneity of prices may cause biases. The EE IO models can be improved into hybrid models by integrating available process LCA data within the model [11,21].

The EE IO side of the reference hybrid LCA model of the study is based on the EE IO model of the Finnish economy created by the Finnish Environment Institute. The model is called ENVIMAT [4], and the consumption version of the model uses the same COICOP classification as the Household Budget Survey. The ENVIMAT model includes 50 aggregated consumption categories. The model is a single-region model, but it has the general weakness of such models in assuming that the domestic production of imports [21] is corrected with the trade data from the main trade partners of Finland [4,42].

The average emissions caused by the combustion phase of energy production were 209 CO_2 kg/MWh for district heating and 223 CO_2 kg/MWh for electricity in 2012 in Finland, according to Motiva [43]. In the reference model, however, the actual local emissions caused by the cities' power plants and heating boilers in 2012 are employed to assess city-specific emissions, to integrate the process LCA perspective, and to assess the carbon footprints of the direct energy use of a city resident. The local energy system emissions were based on the fuel consumptions of a city's energy systems [44], topped up with the Finnish average upstream emissions based on the ENVIMAT model [4].

Housing energy consumption, calculated according to the Household Budget Survey and energy prices in Finland for the survey year, forms the direct stationary energy consumption of a city resident in the study. The rest of the local energy consumption, the indirect part due to consumption of locally produced goods and services, cannot directly be allocated to the city's energy system, since the majority of the energy is embodied in imports from outside the city. Thus, national averages are used for the indirect component. The actual GHG emission impact of the local energy provider is greater than this, as discussed later in the paper. Furthermore, in cases where the local energy production does not cover the direct energy consumption of housing energy, national average values are used for the missing part.

The reference model, which is a traditional carbon footprint model, excludes the emissions of municipal energy production when it exceeds the demand of housing energy. In practice, this energy is consumed either within the cities' other energy consumption categories, within a country, or within other countries in a system. As this energy is supplied to a system with larger boundaries than a city, particularly the electricity grid, it is not justified to be allocated to other consumption categories within a city even though they are connected to the same system. Justification to allocate municipal energy production emissions to the housing energy category comes from the design principal where municipal energy production is sized to fulfill the demand from housing energy consumption and its heat demand in particular. In order to gain a more comprehensive understanding of the cities' total GHG emission contribution, so-called excess municipal energy is calculated and presented; it represents emissions caused by municipal energy production, which is not allocated to the housing energy category.

The method chosen for allocating emissions within combined heat and power (CHP) production to electricity and heat is the benefit allocation method [45,46]. In the benefit method, the emissions of a CHP plant are divided in accordance with the conversion efficiencies of alternative separate production forms. For electricity, the alternative production form is a condensing power plant with a fixed efficiency of 39%, and for heat, a heating boiler with a fixed efficiency of 90%. The benefit is allocated to both end fractions. In the calculation, first the fuel consumption of alternative acquisition forms is calculated by dividing the produced energy form in the cogeneration by the efficiency of the separate production of energy form.

$$F'_e = \frac{E_e}{\eta_e} \quad (1)$$

$$F'_h = \frac{E_h}{\eta_h} \quad (2)$$

where F'_e = fuel consumption of an alternative acquisition form for electricity; F'_h = fuel consumption of an alternative acquisition form for heat; E_e = produced electricity in cogeneration; E_h = produced heat in cogeneration; η_e = efficiency of separate production of electricity (39%); η_h = efficiency of separate production of heat (90%).

The actual fuel consumption allocated to an end energy fraction is calculated with the ratio of the primary energy used to produce it with the separate energy production and the primary energy needed to produce both the energy fractions with the separate production forms.

$$F_e = \frac{F * F'_e}{F'_e + F'_h} \quad (3)$$

$$F_h = \frac{F * F'_h}{F'_e + F'_h} \quad (4)$$

where F_e = calculated fuel consumption of electricity production in cogeneration; F_h = calculated fuel consumption of heat production in cogeneration; F = consumption of fuel in cogeneration.

2.3. Electricity Grid-Level System Implications

Since the supply and demand of an energy system have to be balanced temporally and spatially, the marginal system impacts are a well-known phenomena of electricity grid and electricity system production. Studies [29,30] have suggested that by altering the electricity consumption at the system level decreases or increases the regulative/marginal capacity in a similar fashion. Studies [31,32,34] have offered similar findings to the perspective that uses a single measure. From the life cycle assessment perspective, it has been discussed that marginal implications should be considered when a consequential life cycle assessment is performed [47,48]. However, it is noted that consequential implications are a complex set of affected technologies rather than being a simple change in marginal capacity [49–51].

The electricity grid—the market and the power generation system—in Finland is organized based on different production technologies, to which increased demand will have a different impact [52]. In Finland, this currently leads to increased use of fossil fuels and emissions per kilowatt-hour when more energy is required by the system, as the regulating power plants are based on fossil fuels. This phenomenon is defined in the study as marginal energy production (MEP). Accordingly, the energy efficiency improvements, low emission investments, and energy conservation measures benefit the system when they decrease the MEP. The country's electricity grid is not isolated; it is connected to neighboring countries. The possible effects from such international grid connections are discussed in the Discussion section.

Although heat demand is the dominant factor driving energy production in Finland, in some cases this can be the market price of electricity as well. In the study, it is assumed that the heat demand leads to the generation of CHP electricity, which is supplied to the electricity grid, which again replaces MEP production that is otherwise required. Although MEP is a set of different technologies and production units, the MEP in the research area and target year, Finland 2012, was for the most part condensation technology based on coal power generation [44]. In this study, a plant-level conversion efficiency of 39% was used for MEP production with 4% of transmission losses and 86 CO_2 kg/MWh for upstream emissions [4]. Values are average values of the Finnish system and do not represent actual plant-level values. This is justified, since the purpose is to analyze the overall development dynamically, and thus the single plant-level values are irrelevant.

The electricity grid energy-system level implications are presented from two perspectives. First, the initial system implications in the reference year of 2012 are presented. The presented results are the differences between emissions from the electricity generated by the city and the substituting MEP. Emissions are calculated based on the benefit distribution method described earlier, while an alternative MEP in 2012 is defined to be condensing coal, as presented earlier. The results thus show the increased or decreased emissions at the system level if the municipal electricity production were substituted by MEP.

The second perspective incorporates the temporal development of MEP according to anticipated de-carbonization policies [53]. Similar to the whole energy system, the MEP is anything but stationary. The energy supplied to the grid displaces the continuously improving MEP, and thus the benefits of the excess energy from CHP production is reduced increasingly as the MEP improves. National targets are to reduce emissions from energy production by 80–95% by the year 2050 [53]. These targets are cross sectoral and they drive marginal technology accordingly. Although in reality improvements are gradual, here they are set to decrease MEP emissions by 6% (linearly) annually until 2050. The reference point of local energy generation is set as stationary to highlight the development needs from this perspective. Here again the presented results are the differences between the emissions from electricity generated by the city and the substituting MEP, but with annually decreasing emissions. Similarly to the first perspective, the emissions are calculated based on a benefit distribution method.

3. Results

Results are presented and discussed in two parts. First, the contribution of the municipal energy system to the carbon footprint of city residents (reference carbon footprint model) is presented and further reflected against the excess GHG emissions of the municipal energy systems. Second, electricity grid level (i.e., consequential) system impacts are presented, and their relevance to climate change mitigation is discussed.

3.1. City Carbon Footprints and GHG Emissions of Municipal Energy System

In Figure 1, the left-hand columns show the reference carbon footprints of city residents. The average carbon footprint is 10,184 CO_2-eq kg/year per capita, ranging between 7853 and 11,960 CO_2-eq kg/year per capita. Cities such as Lappeenranta, Hämeenlinna, and Kotka are showing relatively low carbon footprints for city residents, whereas cities such as Espoo, Turku and Kouvola show relatively high carbon footprints for city residents. Cities are listed based on the number of city residents.

The most significant contributor to GHG emissions is the municipal housing energy category, followed by food consumption with a slightly lower contribution. Next are tangibles, the housing–other category, motor fuels, non-municipal housing energy, services, public transportation, and personal vehicles—other category, in that order. The differences between cities are not due to their size or any other single dominant factor. The strongest correlation is between the municipal housing energy category and the city resident's carbon footprint, and this peaks in the carbon footprint in Kouvola. Purchased services and income level correlate with higher carbon footprints, which is the especially evident in large cities such as Helsinki, Espoo, Vantaa, Tampere, and Turku. Motor fuel usage is the lowest for the densest city (Helsinki), but the differences in motor fuel use explain only a fraction of the overall carbon footprints.

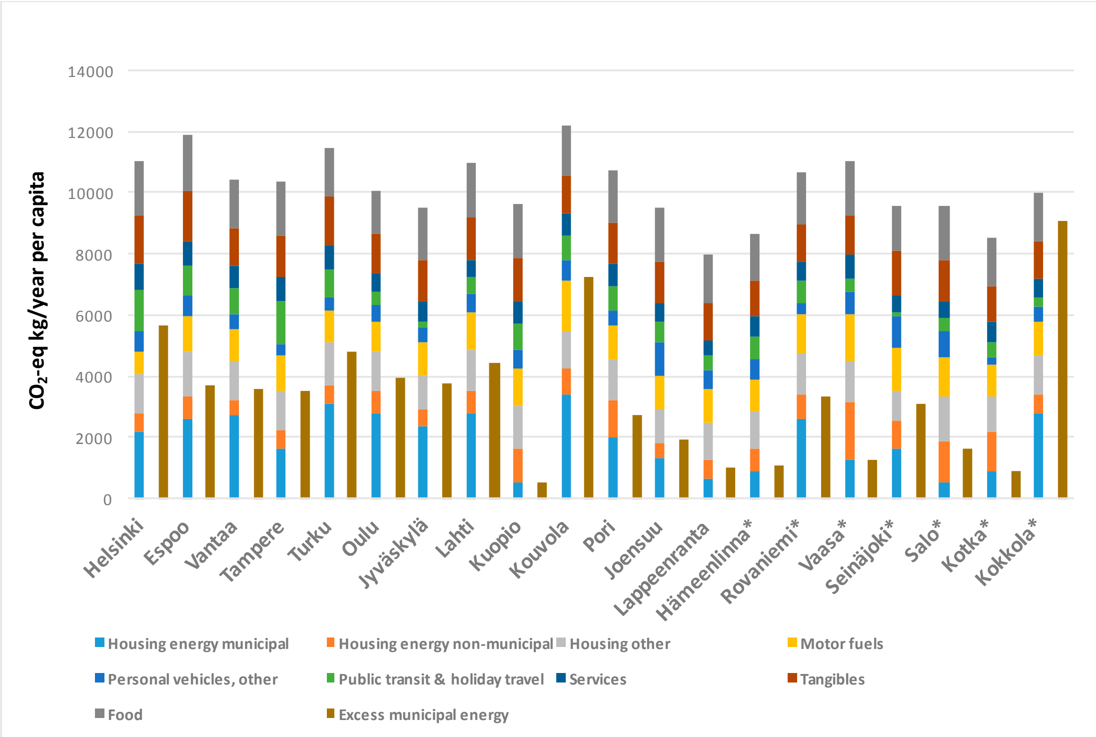

Figure 1. Reference carbon footprint model and GHG emissions of excess municipal energy. Cities with sample size below 50 households are marked with *.

The contribution of municipal energy production in city residents' carbon footprint is relatively low, with an average share of 18%, ranging from 5% to 28%. The rest of the emissions in the housing energy category comes from supplementing electricity from the national grid and from fuels used for heating in individual buildings. The average contribution of the complete housing energy category is 28%, ranging from 16% to 35%.

Figure 1 also shows the excess municipal emission category, which includes emissions from municipal energy production that is not allocated to the housing energy category; this is shown as single-colored bar to the right of each city's carbon footprint per capita. While the contribution from the housing energy category reached an average of 28% in the consumption-based accounting, the total GHG emissions of municipal energy production (i.e., housing energy plus excess municipal energy) is far more significant in some cities, reaching an average of 32%, ranging from 6% all the way to 91%. The reason for such a wide range is due to the locations of the national or industrial electricity production plants. GHG emissions of these plants are shown in the national and international level in the consumption-based carbon footprint assessment but are recognized when municipal production based GHG assessment is performed. As they are not justified to be allocated for a city resident, it is advantageous when assessing the complete potential for a city to reduce absolute GHG emissions.

3.2. Consequential Energy System Implications

Figure 2 presents the consequential energy system implications due to power production in local CHP plants as described in Section 2.2. All the cities have negative values, which indicates that municipal electricity production decreases the emissions of the national grid. This might be surprising, as the yearly emissions of the municipal energy system per kWh are higher than the average emissions in Finland. But since the municipal excess energy is replacing the carbon intensive MEP, at least the short-term implications are shown as positive.

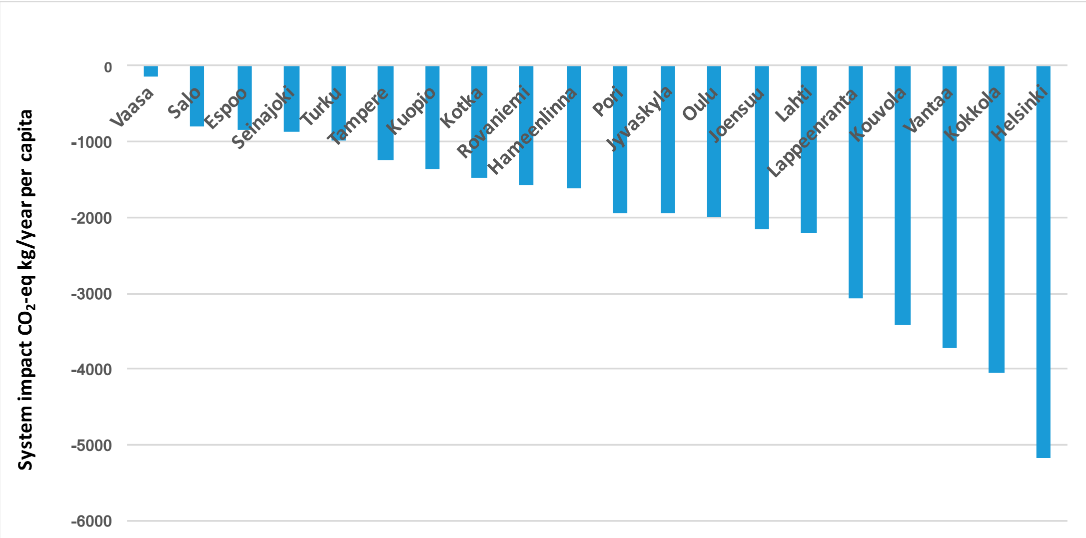

Figure 2. Initial 2012 marginal system-level emission decrease implications.

The national electricity grid level system implications further emphasize the importance of municipal energy systems. In cities such as Helsinki and Kokkola, these positive short-term consequential electricity system impacts are massive—up to 5000 CO_2-eq kg per capita GHG emissions, equaling some 50% of the residents' carbon footprint. For the whole set of evaluated cities, the carbon footprints increase in range from 13% to 47% when the consequential implications of MEP are allocated to city residents.

Even though the short term consequential impacts have very positive implications, it is shown in Figure 3 that with the long-term scenario, the positive implications are being quickly diluted. Here the initial marginal system-level emission decrease implications are assessed annually to replace the annually developed MEP. The MEP is decarbonizing itself quickly, and thus the excess municipal energy no longer has such a relative benefit. Some cities (such as Vaasa, Espoo, and Turku) will lose the relative benefits as early as 2020. Similarly, when moving towards 2050, all the municipals lose their relative energy system benefits due to improvements in MEP.

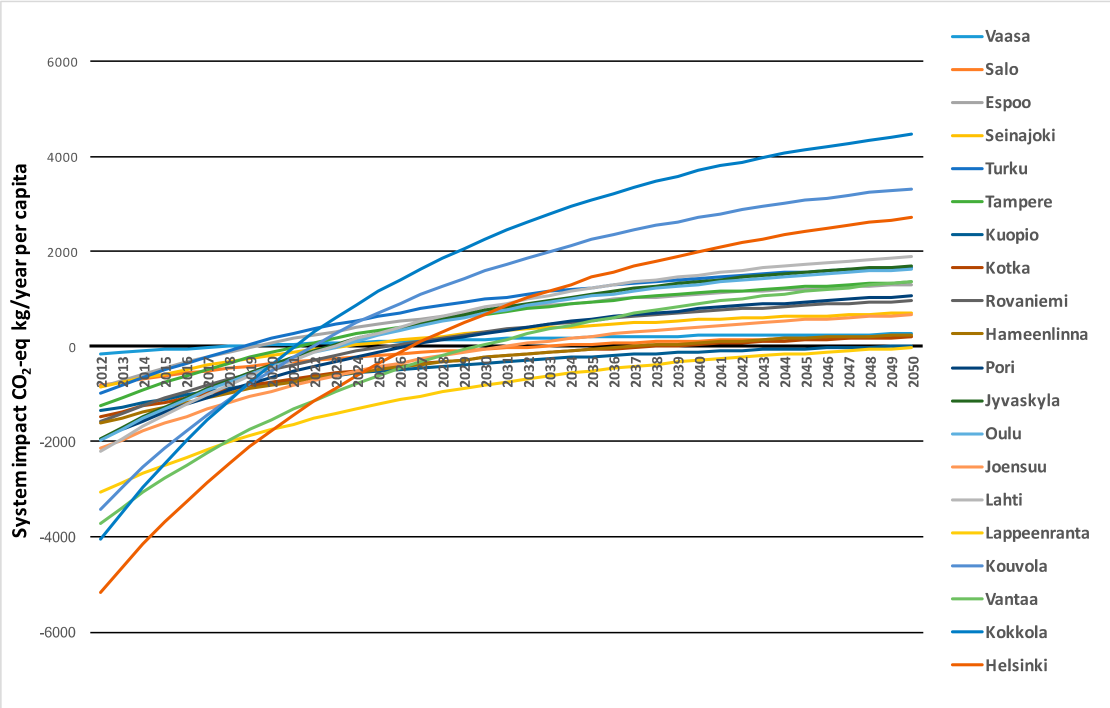

Figure 3. MEP simulation of consequential carbon footprint implications up to 2050.

4. Discussion and Conclusions

The paper studied the role of municipal energy systems in the consumption-based carbon footprint assessment of a city resident in Finland. In consumption-based carbon footprint models, where energy is typically included as national or regional averages with constant GHG intensity, the immediate importance of the municipal energy system is limited.

It was found that in the consumption-based carbon footprint assessment, the municipal energy for only 18% of the carbon footprint contribution on average, ranging from 5% to 28% between different cities. When all the local energy production was allocated to city residents through consumed products and services, the average contribution was 32%, ranging from 6% to as high as 91%.

Although the contributions of municipal energy systems were shown to be somewhat limited on consumption-based carbon footprints, the consequential electricity system implications increase the importance significantly. Within the reference year 2012, the carbon footprints would have been 13% to 47% higher without municipal CHP energy production due to the required MEP where the consequential utilization of alternative energy sources are allocated to city residents. However, when the electricity grid's production portfolio evolves over time, the positive effect of municipal energy production is diluted relatively quickly, thus emphasizing the importance of continuously improving the municipal energy system. Based on this study, it can be concluded that the highest potential to decrease emissions within a city boundary or a larger system boundary is in cities that have an existing large production capacity utilizing fossil fuels. The largest cities generally have the highest emission decrease potential, and Helsinki has by far the most. However virtually any city can introduce new low emission capacity to decrease system emissions and the carbon footprint of a city resident.

In comparison to previous consumption-based carbon footprint studies [12–20], the system implications of an integrated assessment provide a more comprehensive outlook for the consequential GHG implications within the larger system boundary. The system-implication results re-emphasize the role of municipal energy systems in climate change mitigation, even though all the benefits may not be directly allocated to city residents.

In line with numerous studies regarding energy-system-level implications [29–38], our results highlight the relevance of marginal system implications. These studies have mainly focused on single measures, short-term implications, or general implications, while our study has focused on municipal planning and municipal energy planning. In comparison to the results of previous studies, our results underline the importance of long-term system development as well as the potential system implications resulting from municipal planning and measures.

Even though this integrated assessment model provides a more comprehensive outlook, it is nevertheless not entirely inclusive. Uncertainties and limitations exist in three different areas. First, the boundary selection is still chosen, and this limits the understanding of the system implications at an even larger system level. In practice, the case setting is always part of global energy ecosystems, where system implications are also present. In this case, the electricity system is already connected internationally, and actions within countries' grids are having implications for other countries' grid import and export distributions. The presented research did not include these implications. Second, simulations include scenarios for system evolution. When system scenarios and estimations are made, there are always uncertainties involved. In practice, this means that cities planning their municipal energy systems within a larger energy system must recognize that the municipal energy system may shift towards being emission-increasing from the system perspective, either sooner or later than predicted. Third, the accuracy of the simulation and energy system implications within the research simulation is limited. Temporal and spatial details increase the variations in the actual system implications.

In addition, the initial assumptions for simulations limit the outlook of possible real-life scenarios. If the municipal CHP capacity would not exist, the supply and demand balance in the market would be different and an alternative new capacity could also be introduced. This could mean investments into a more sustainable capacity than the MEP capacity and even the average capacity. Moreover, it is highly unlikely that the municipal energy sector would be left undeveloped, although the objective was to present the temporal development need for such a system.

The consequential system implications generated by municipal energy systems are highly important from the perspective of national and global greenhouse gas emissions. From the perspective of municipal energy planning and the consumption-based carbon footprints of city residents, the outlook may indicate otherwise. Thus, it would be necessary that an understanding of the consequential implications is utilized within the processes and organizations dealing with municipal planning. More research is needed in order to improve the applicability of the method in practical municipal-level planning.

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Author Contributions: Jani Laine conducted the system impact assessment, created the research design, and participated in all stages of preparing the manuscript. Juudit Ottelin conducted the baseline carbon footprint assessment. Jukka Heinonen established the research frame and participated in all stages of preparing the manuscript. Seppo Junnila participated in research framing and was consulted in all the stages of preparing the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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