Department of Built Environment

The significance of municipal energy related actions when aiming at carbon neutral cities

---

Jani Laine

Aalto University

UNIVERSITY OF ICELAND

DOCTORAL DISSERTATIONS

Jani Laine

The significance of municipal energy related actions when aiming at carbon neutral cities

Aalto University

2021

Aalto University publication series
DOCTORAL DISSERTATIONS 25/2021

The significance of municipal energy related actions when aiming at carbon neutral cities

Jani Laine

A doctoral dissertation completed for the degrees of Doctor of Science (Technology) and Philosophiae Doctor in Environmental Studies to be defended, with the permission of the Aalto University School of Engineering and University of Iceland School of Engineering and Natural Sciences, https://aalto.zoom.us/j/62564164704, on 5th March 2021.

This doctoral dissertation is conducted under a convention for the joint supervision of dissertation at Aalto University, Department of Built Environment, and University of Iceland, Faculty of Civil and Environmental Engineering.

University of Iceland
School of Engineering and Natural Sciences Faculty of Civil and Environmental Engineering

Aalto University
School of Engineering
Department of Built Environment
Real Estate Business

Supervising professors
Professor Seppo Junnila, Aalto University, Finland
Professor Jukka Heinonen, University of Iceland, Iceland

Ph.D. Committee (University of Iceland)
Professor Jukka Heinonen (Chair)
Professor Guðmundur Freyr Úlfarsson
Professor Seppo Junnila, Aalto University

Thesis advisors

Preliminary examiners
Docent, PhD Laura Saikku, Finnish Environment Institute (SYKE)
Professor, PhD André Bohne, NTNU, Norway

Opponent
Docent, PhD Laura Saikku, Finnish Environment Institute (SYKE)

Aalto University publication series
DOCTORAL DISSERTATIONS 25/2021

ISBN 978-952-64-0282-6 (printed)
ISBN 978-952-64-0283-3 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)
http://urn.fi/URN:ISBN:978-952-64-0283-3

Unigrafia Oy
Helsinki 2021

Finland

NORDIC SWAN ECOLABEL
Printed matter
4041-0619

A? **Aalto University**

Abstract

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Author
Jani Laine

Name of the doctoral dissertation
The significance of municipal energy related actions when aiming at carbon neutral cities

Publisher School of Engineering

Unit Department of Built Environment

Series Aalto University publication series DOCTORAL DISSERTATIONS 25/2021

Field of research Real Estate Business

Manuscript submitted 14 August 2020 **Date of the defence** 5 March 2021

Permission for public defence granted (date) 15 February 2021 **Language** English

☐ **Monograph** ☒ **Article dissertation** ☐ **Essay dissertation**

Abstract

This dissertation discusses the implications of municipal energy-related actions in the generation of low carbon and carbon neutral cities. The purpose of the study is to examine the implications of these actions within the boundaries of scope 2 - 3 (according to the GHG Protocol) and from a consequential system implication perspective. This dissertation considers municipal energy systems to be energy systems which are located within the city boundaries, or within wider boundaries where municipalities may have an impact through ownership or similar arrangements. The energy sector convers electricity and heat supplies, thus excluding fuel supplies which are not related to the former.

This dissertation consists of four peer-reviewed scientific journal papers. The research utilized a lifecycle approach to identify system implications together with single- and multiple case studies as well as semi-constructed interviews as research methods. Finnish cities and their energy systems were studied throughout the dissertation studies.

It was identified that municipal energy related actions have a significantly higher importance and greater implications when the boundaries are extended from scope 1 of the GHG Protocol and the attributional life cycle assessment to scope 2 and 3 of the GHG Protocol together from a consequential life cycle assessment perspective. Generally, cities' role in scope 3 GHG emissions is significant. Even more so when marginal production implications are considered. These implications can lead to either significantly lower or higher system level GHG emission regardless even when the initial aim is to reduce GHG emissions. Examining the marginal energy system implications is a powerful method for cities to reduce their GHG emissions within the city and within wider boundaries. Examining such implications could be utilized to compensate for GHG emissions within sectors which find it more difficult to take actions to directly reduce their GHG emissions. Still the utilization and recognition of these implications together with their potential is seen to be lacking in carbon neutral city processes. Bettter understanding scope 2 and 3 system implications offer great potential for cities to reduce their GHG emissions within such boundaries as they aim to achieve low carbon and carbon neutral cities.

Keywords Carbon neutral city, life cycle assessment, energy systems

ISBN (printed) 978-952-64-0282-6 **ISBN (pdf)** 978-952-64-0283-3

ISSN (printed) 1799-4934 **ISSN (pdf)** 1799-4942

Location of publisher Helsinki **Location of printing** Helsinki **Year** 2021

Pages 111 **urn** http://urn.fi/URN:ISBN:978-952-64-0283-3

Aalto-yliopisto

Tiivistelmä

Aalto-yliopisto, PL 11000, 00076 Aalto www.aalto.fi

Tekijä
Jani Laine

Väitöskirjan nimi
Kunnallisien energiajärjestelmien merkitys hiilineutraaleissa kaupungeissa

Julkaisija Insinööritieteiden korkeakoulu

Yksikkö Rakennettu Ympäristö

Sarja Aalto University publication series DOCTORAL DISSERTATIONS 25/2021

Tutkimusala Kiinteistöliiketoiminta

Käsikirjoituksen pvm 14.08.2020 **Väitöspäivä** 05.03.2021

Väittelyluvan myöntämispäivä 15.02.2021 **Kieli** Englanti

☐ **Monografia** ☒ **Artikkeliväitöskirja** ☐ **Esseeväitöskirja**

Tiivistelmä

Tässä väitöskirjassa tarkastellaan kunnallisten hiilineutraaliuteen tähtäävien energiapäätösten vaikutuksia. Tutkimuksen tarkoituksena on tunnistaa näiden vaikutuksia GHGProtocol:n taserajojen scope 2 ja 3 sisällä, kaupungin rajojen ulkopuolella, seuraamuksellisen elinkaariarvioinnin näkökulma huomioiden. Väitöskirjassa kunnallinen energiajärjestelmä nähdään kaupungin rajojen sisäiseksi energiajärjestelmäksi tai sellaiseksi johon kunnalla on vaikutusmahdollisuus omistajuuden tai vastaavan järjestelyn kautta. Väitöskirjan energiajärjestelmät ja -sektori rajataan sähkö ja lämpöliiketoimintaan näin myös poislukien polttoainetoimitukset jotka eivät liity näihin.
Väitöskirja koostuu neljästä vertaisarvioidusta julkaisusta. Tutkimus hyödyntää elinkaariarvioinnin näkökulmia vaikutuksien arvioinnissa sekä käyttää tutkimusmenetelminä tapaustutkimuksen keinoja sekä puolistruturoitua haastattelua. Tapaustutkimuksien tutkimuskohteina tarkasteltiin suomalaisia kaupunkeja.
Tutkimuksessa tunnistettiin kunnallisien energiaan liittyvien toimenpiteiden huomattavan paljon suurempi merkitys kun scope 1, eli kaupungin sisäistä, taserajaa laajennettiin scope 2:een ja 3:een, kattamaan kansalliset suorat ja epäsuorat päästövaikutukset, sekä huomioitiin seuraamuk-sellinen elinkaari näkökulma atributionaalisen lisäksi. Seuraamuksellisella näkökulmalla huomi-oidaan vaihtoehtoisten energiatuotantomuotojen vähentyminen tai kasvu. Yleisesti kaupunkien merkitys kansallisella epäsuorat päästöt huomioivalla scope 3 taserajalla on keskeinen. Kun huo-mioidaan marginaalisen energiatuotannon vaikutukset, merkitys kasvaa entisestään. Nämä vai-kutukset voivat johtaa joko huomattavasti pienempiin tai suurempiin järjestelmätason kasvihuonekaasumuutoksiin vaikka tarkoituksena olisi ollut pienentää kasvihuonekaasukertymää. Marginaalituotannon muutosten tarkastelu laajemmin kuin kaupungin rajojen sisällä tarjoaa kunnille tehokkaan keinon vähentää kunnallisia sekä kansallisia kaskvihuonekaasuja. Näillä vaikutuksilla voitaisiin mahdollisesti kompensoida myös niiden sektoreiden päästöjä joihin on hankala kohdistaa suoria päästövähennystoimenpiteitä kun tähdätään yksittäisen kaupungin hiilineutraaliuteen. Kuitenkaan näitä vaikutuksia laajemmilla taserajoilla ja marginaalienergiatuotannossa ei vielä tunnisteta vaikka ne tarjoavat tehokkaita keinoja kasvihuonekaasujen vähentämiseen kehittäessä hiilineutraaleita kaupunkeja sekä hiilineutraalia yhteiskuntaa.

Avainsanat Hiilineutraali kaupunki, elinkaariarviointi, energiajärjestelmät

ISBN (painettu) 978-952-64-0282-6 **ISBN (pdf)** 978-952-64-0283-3

ISSN (painettu) 1799-4934 **ISSN (pdf)** 1799-4942

Julkaisupaikka Helsinki **Painopaikka** Helsinki **Vuosi** 2021

Sivumäärä 111 **urn** http://urn.fi/URN:ISBN:978-952-64-0283-3

Aalto University

Útdráttur

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Höfundur
Jani Laine

Heiti doktorsritgerðar
The significance of municipal energy related actions when aiming at carbon neutral cities

Útgefandi Verkfræðisvið

Svið Fasteigna-, skipulags- og landupplýsingadeild

Ritröð Útgáfurit Aalto-háskólans – DOKTORSRITGERÐIR 25 /2021

Rannsóknasvið Fasteignaviðskipti

Heimild til birtingar (dagsetning) 15.2.2021 **Dagsetning doktorsvarnar** 5.3.2021

Tungumál Enska.

☐ **Sérrit** ☒ **Doktorsritgerð úr fræðigreinum (samantekt + upprunalegar fræðigreinar)**

Útdráttur
Í þessari ritgerð er fjallað um afleiðingar orkutengdra aðgerða sveitarfélaga við myndun lágkolefnis- og kolefnishlutlausra borga. Tilgangur rannsóknarinnar er að kanna afleiðingar þessara aðgerða innan umfangs 2-3 (samkvæmt GHL viðmiðunarreglunum) og út frá sjónarhorni kerfisáhrifa. Ritgerð þessi telur orkukerfi sveitarfélaga vera orkukerfi sem eru staðsett innan borgarmarkanna, eða innan víðari landamæra þar sem sveitarfélög geta haft áhrif með eignarhaldi eða svipuðu fyrirkomulagi. Orkugeirinn nær yfir rafmagn og hitaveitu og undanskilur eldsneyti sem ekki tengist því.
Ritgerð þessi samanstendur af fjórum ritrýndum greinum í vísindatímaritum. Rannsóknirnar notuðust við vistferilsgreiningar sem rannsóknaraðferð til að greina kerfisáhrif, auk einstakra og margþættra tilviksrannsókna sem og hálfskipulagðra viðtala. Finnskar borgir og orkukerfi þeirra voru rannsakaðar.
Komist var að því að orkutengdar aðgerðir sveitarfélaga hafa verulega hærra vægi og meiri áhrif þegar kerfismörkin eru víkkuð frá umfangi 1 í GHL viðmiðunarreglunum í umfang 2 og 3. Almennt er hlutverk borga hvað varðar losun á GHL í umfangi 3 verulegt, og enn frekar þegar litið er á áhrif jaðarframleiðslu. Afleiðingarnar eru að ýmist er verulega minni eða meiri losun á GHL sama hvort að upphaflegt markmið sé að draga úr losun GHL. Að skoða áhrif jaðarorkukerfisins er öflug aðferð fyrir borgir til að draga úr losun GHL innan borgarinnar og innan víðari landamæra. Hægt væri að skoða slíkar afleiðingar til að bæta upp losun GHL innan greina sem eiga erfiðara með að grípa til aðgerða til að draga beint úr losun GHL. Enn er litið svo á að notkun og viðurkenning þessara afleiðinga ásamt möguleikum þeirra sé ábótavant í kolefnishlutlausum borgarferlum. Betri skilningur á umfangi kerfisáhrifa 2 og 3 býður upp á mikla möguleika fyrir borgir að draga úr losun GHL innan slíkra marka þegar þær miða að því að ná kolefnishlutleysi í borgum.

Lykilorð Carbon neutral city, life cycle assessment, energy systems

ISBN (prentað eintak) 978-952-64-0282-6 **ISBN (pdf)** 978-952-64-0283-3

ISSN (printed) 1799-4934 **ISSN (pdf)** 1799-4942

Útgáfustaður Helsinki **Prentstaður** Helsinki **Ár** 2021

Blaðsíðufjöldi 111 **urn** http://urn.fi/URN:ISBN:978-952-64-0283-3

Acknowledgements

The purpose of this doctoral thesis was to bring something new, useful and valuable for all of us in order to make sustainable living possible without limiting possibilities of development and growth. To make such a living possible, enormous efforts needs to be made and a doctoral thesis can advance this only little if any. However, if possibility to advance common good even remotely exist one needs to seize that.

To make this possibility reality, I would like to thank my supervising professor Seppo Junnila. It has been a pleasure and honor to work with you. I'm thankful for all the wide-range discussions and generally time spent together. I'm also happy that I can call you a friend as well.

Another person to whom I'm deeply grateful is my good friend and thesis advisor professor Jukka Heinonen. Jukka is by far generally most efficient person I know wherever he chooses to be.

Next, I would like to thank all the cowriters of the research papers. Thank you friends and team members Jussi, Petri, Ali, Juudit, Eerika, Vitalija, Lauri, Sanna and Eeva. I'm especially grateful for my close friends Kaisa and Antti who have also supported this doctoral thesis project.

Also, I'm thankful for thesis pre-examiners professor André Bohne and Docent, PhD Laura Saikku who supported highly valuable feedback which helped to finalize the dissertation and to address the contribution of the dissertation more clearly.

Finally, thanks for my family and friends who are listed above for the support.

Contents

List of Abbreviations and Symbols

ALCA	Attributional life cycle assessment
BAU	Business as usual
CHP	Combined heat and power
CLCA	Consequential life cycle assessment
CN	Carbon neutral
EE IO	Environmentally extended input-output
GHG	Greenhouse gas
HP	Heat pump
IEA	International energy agency
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental panel on climate change
LCA	Life cycle assessment
MEP	Marginal energy production

List of Publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals.

1. Laine, J; Ottelin, J; Heinonen, J & Junnila, S. 2017. Consequential Implications of the Municipal Energy System on City Carbon Footprints, Sustainability, vol. 9, no. 10, 1801. Level 1 [Publication forum 2020]

2. Heinonen, J; Laine, J; Pluuman, K; Säynäjoki, E-S; Soukka, R & Junnila, S. 2015. Planning for a Low Carbon Future? Comparing Heat Pumps and Cogeneration as the Energy System Options for a New Residential Area, Energies, vol. 8, no. 9, pp. 9137-9154. Level 1 [Publication forum 2020]

3. Laine, J; Kontu, K; Heinonen, J & Junnila, S. 2020. Uncertain Greenhouse Gas Implications in Waste Heat Utilization – A Case Study with a Data Center, Journal of Sustainable Development of Energy, Water and Environment Systems, vol. 8 no. 2. pp 360-372. Level 1 [Publication forum 2020]

4. Laine, J; Heinonen, J; Junnila, S. 2020. Pathways to Carbon-Neutral Cities Prior to a National Policy. Sustainability, vol. 12, no. 6. 2445. Level 1 [Publication forum 2020]

Author's Contribution

Publication 1: Consequential implications of municipal energy system on city carbon footprints

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

Publication 2: Planning for a Low Carbon Future? Comparing Heat Pumps and Cogeneration as the Energy System Options for a New Residential Area

Jukka Heinonen conducted the assessments and wrote the main part of the paper. Jani Laine participated in the research design and the assessments, collected background data and helped write parts of the paper. Karoliina Pluuman collected data, conducted the initial calculations and helped write parts of the paper. Eeva Säynäjoki, Risto Soukka and Seppo Junnila were consulted about the research design and commented on the manuscript during the writing process.

Publication 3: Uncertain Greenhouse Gas Implication in Waste Heat Utilization – A Case Study with a Data Center

Jani Laine conducted the research assessment, created the research design, and participated in all stages of the manuscript preparation. Kaisa Kontu conducted the energy research positioning and participated in all stages of the manuscript preparation. Jukka Heinonen and Seppo Junnila participated in the research framing and participated in all stages of the manuscript preparation.

Publication 4: Pathways to Carbon-Neutral Cities Prior to a National Policy

Jani Laine took the main responsibility and created the conceptualization. Seppo Junnila and Jukka Heinonen provided comments and discussion.

1. Introduction

1.1 Background

Global warming is one of the largest threats to mankind [IPCC 2018]. Anthropogenic and fossil fuel-based greenhouse gas (GHG) emissions have been identified as a main factor in furthering global warming [IPCC 2018]. Cities account for 70% off anthropogenic GHG emissions [IEA 2008]. Of these anthropogenic GHG emissions, the majority are due to the use of energy [Bruckner et al. 2014] Thus, the role of cities, and their impact on energy use, is crucial in GHG mitigation and preventing global warming.

Within city boundaries, some cities are efficiently following national energy policy [e.g. Sperling et al. 2011, Nilsson & Mårtensson 2003]. Still, the need to further integrate energy and urban planning has been raised in numerous publications [e.g. Vandevyvere & Stremke 2012, Nystedt, Å.; Sepponen 2011, Torabi et al. 2017, Stoeglehner et al. 2011, Madlener & Sunak 2011, Park & Andrews 2004]. The knowhow needed to integrate energy planning within urban planning processes has been suggested to be too limited, and it has been raised that tools which cities could utilize to address such issues can be rather limited [Hedman 2016]. In addition, cities often manage their environmental performance from the energy efficiency perspective, which can lead to negative rebound effects [e.g. Galvin 2014, Turner 2009, Brännlund et al. 2007, Greening et al. 2000, Berkhout et al. 2000].

When extending the city boundary limits to include emissions occurring outside the city but caused by actions within the city, the potential for GHG mitigation has been questioned in several studies [Satterthwaite 2008, Hoornweg et al. 2011, Dodman 2009, Sovacool & Brown 2010]. The main reason for the lack of potential is due to generation of GHG emissions outside the city boundaries and out of city's jurisdiction although the consumption of commodities within the city boundaries is the reason driving these emissions.

Cities' GHG accountment varies based on the selected boundaries and scope of emission sources. Various accountment methods and standards exist such as C40 Cities [C40 Cities 2019], the GHG Protocol [GHG Protocol 2014] and the Covenant of Mayors [Covenant of Mayors 2020]. Regardless of the standard used, cities often account for their GHG emissions based on production and only the GHG emissions which have occurred and are emitted within city boundaries are accounted for, potentially complemented with grid electricity and heat production outside the city. Another method is consumption based GHG accountment, which includes the earlier mentioned GHG emissions outside the city boundary, which is proposed as an alternative for instance by C40 Cities [C40 Cities 2019]. This method allocates all the GHG emissions which have occurred due to consumption within city boundaries for the city, even if the emissions have occurred outside the city boundaries.

The private sector consumption of different commodities and their GHG implications is hard to control by a city when these are not directly influenced by municipal energy production or other infrastructure [e.g. Afionis et al. 2017]. This limits cities' potential for consumption based GHG mitigation. On the other hand, cities are connected into national and global energy networks where they can perform actions which may have GHG mitigation implications and they may implement actions leading to carbon compensation [e.g. Laine et al. 2017].

To specify GHG emissions occurring within different boundaries, the GHG Protocol describes 3 scopes of emissions [GHG Protocol 2014]. Scope 1 GHG emissions are emissions from sources located within a city's boundaries. Scope 2 GHG emissions are emissions which have occurred due to the grid-supplied energy from outside the city's boundaries. Scope 3 GHG emissions are the rest of the GHG emissions which have occurred as a consequence of the consumption within city boundaries. These emissions include for instance emissions from the energy infrastructure, out-of-boundary transportation, and waste treatment as well as other indirect emissions. Scope 3 emissions also include GHG emissions from city residents' consumption of commodities. Figure 1 illustrates the scope definition in the GHG Protocol.

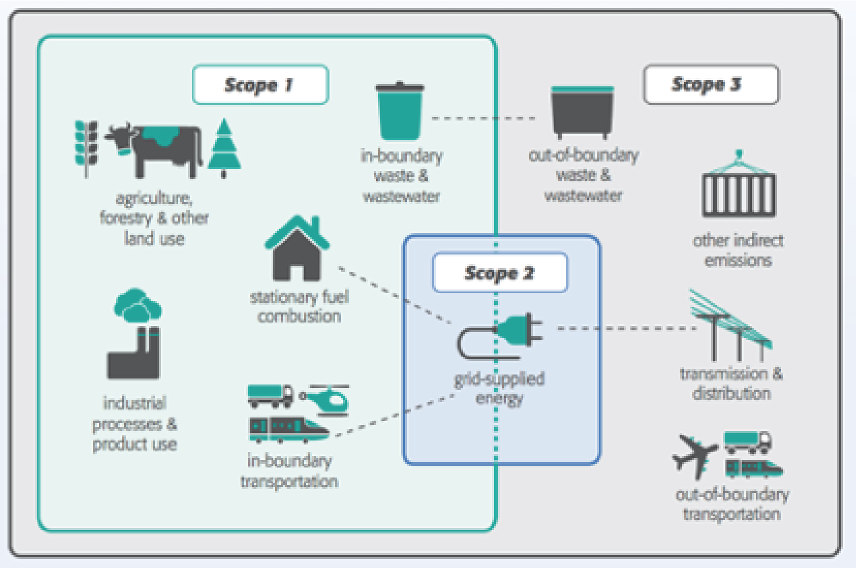


Figure 1. Scope definition in the GHG Protocol [GHG Protocol 2014].

Globally, cities such as Berlin [City of Berlin 2019], London [City of London 2019], Copenhagen [City of Copenhagen 2019], Stockholm [City of Stockholm 2019] and New York [City of New York 2019] have committed to carbon neutrality. Of these cities New York, Berlin and London have set a target year of 2050 to achieve this. Stockholm has set the target year of 2040 and Copenhagen

2025. When specifying what a carbon neutral city is, the definition by Cities C40 [C40 Cities 2019] is often followed with the following criteria: 1. net-zero GHG emissions (annual emissions completely cancelled out through carbon offsetting or removed through carbon dioxide removal or emissions removal measures) from fuel use in buildings, transport, and industry (scope 1); 2. net-zero GHG emissions from the use of grid-supplied energy (scope 2); 3. net-zero GHG emissions from the treatment of waste generated within the city boundaries (scope 1 and 3), and 4. where a city accounts for additional sectoral emissions in their GHG accounting boundary, net zero GHG emissions from all additional sectors in the GHG accounting boundary. When following this definition of a carbon neutral city, non-energy commodities produced outside the city boundaries are excluded. This simplifies things and makes a city carbon neutral more easily achievable. The strongest focus is thus on the city's energy supply, both within and outside city boundaries. The Cities C40 network also proposes a consumption-based approach to be used instead, but the described production-based approach is generally utilized by cities. This dissertation practically follows Cities C40 production-based definition for the energy sector in carbon neutrality definition and considers scope 2 and scope 3 emissions with specific definitions defined by individual research papers. One of the research papers considers also consumption-based perspective. Land use, land use change and forest sector (LULUCF) is excluded although its role in bioenergy and carbon balance can be significant. Still, the use of bio-based energy and carbon balance has been discussed in research publication 2.

From the central means how to reach the goal of carbon neutrality, decreasing of energy consumption and increasing of GHG free scope 1 energy production are uniform tools for all cities listed above. Copenhagen also recognizes scope 2 energy production as a central means of reducing GHG emissions. In Finland, where this dissertation's case studies' cities are located, cities such as Helsinki [City of Helsinki 2019], Espoo, Vantaa [City of Vantaa 2019], Tampere [City of Tampere 2019], Turku [City of Turku 2019] and Oulu [City of Oulu 2019] have similar carbon neutral goals. The target year of 2040 has been set by Oulu, 2035 by Helsinki, 2030 by Espoo, Vantaa and Tampere and 2029 by Turku. Similar central means of reducing GHG emissions have been identified, but like Copenhagen, Turku also sees scope 2 energy production as a central means to achieve carbon neutrality. These two cities both have existing municipal energy production outside their city boundaries and have set the carbon neutral target year before the date set for achieving national carbon neutrality. Still, some of the other cities have municipal energy production outside scope 1 but are excluding it and its potential to lower city's GHG emissions.

Where these cities' roadmaps to carbon neutrality are straightforward, they utilize rather simple consumption and emission data as well as bypassing exact plans on how to utilize carbon compensation and offsetting. Whereas municipal district heating is central for all of the cities, the development of large-scale electricity production generally is not. Carbon free electricity production is one of the corner stones for achieving a carbon neutral society and its role is likely to be increased. In reality however, the implications of actions taken regarding the energy system can be complex and hard to predict.

In order to calculate the GHG emissions from different sources a life cycle assessment (LCA) is a practical tool to be used as it captures both the direct and indirect emissions [ISO 2006]. With LCA, two different approaches exist: attributional and consequential forms of LCA (ALCA & CLCA). These two approaches can present two completely different outlooks [e.g. Plevin et al. 2013, Earles & Halog 2011]. From the perspective of energy systems and ALCA, ALCA depicts the potential environmental impacts that can be attributed to a system over its life cycle, i.e. upstream in the supply-chain and downstream following the system's use and end-of-life value chain. Attributional modelling makes use of historical, fact-based, measurable data of known (or at least knowable) uncertainty, and it includes all the processes that are identified to relevantly contribute to the system being studied [JRC-IES 2010]. CLCA aims to identify the consequences that a decision in the foreground system has for other processes and systems of the economy, both in the ana-lysed system's background system and on other systems. It models the ana-lysed system around these consequences. The consequential life cycle model hence does not reflect the actual (or forecasted) specific or average supply-chain, but a hypothetic generic supply-chain is modelled that prognosticates market mechanisms, and potentially includes political interactions and changes in consumer behaviour [JRC-IES 2010]. Thus, consequential system implications for the energy system have impacts on so-called marginal production technology (MEP [e.g. Zivin et al. 2014]. Often the production costs and GHG emissions positively correlate, which means that also municipal energy related actions play an emphasized role in national GHG emissions and in GHG emission reductions in order to achieve carbon neutrality. Numerous studies have been published discussing the role of a merit order and marginal energy technology in energy systems, life cycle assessment and urban development [Holttinen & Tuhkanen 2004, Siitonen et al. 2010, Pehnt et al. 2008, McCarthy & Yang 2010, Olkkonen & Syri 2016, Soimakallio et al. 2011]. However, while MEP and CLCA are well studied, their role in municipal GHG reduction is a rather untouched area. Especially where the research of the carbon neutral cities' generation processes is almost completely lacking, the need to understand and to integrate system implications with this perspective and ambitions exists. Understanding these system implications also requires a perspective which is broader than scope 1 for GHG implications assessment. Figure 1 illustrates the relationships between MEP, ALCA, CLCA and carbon neutral cities as perceived in the dissertation.

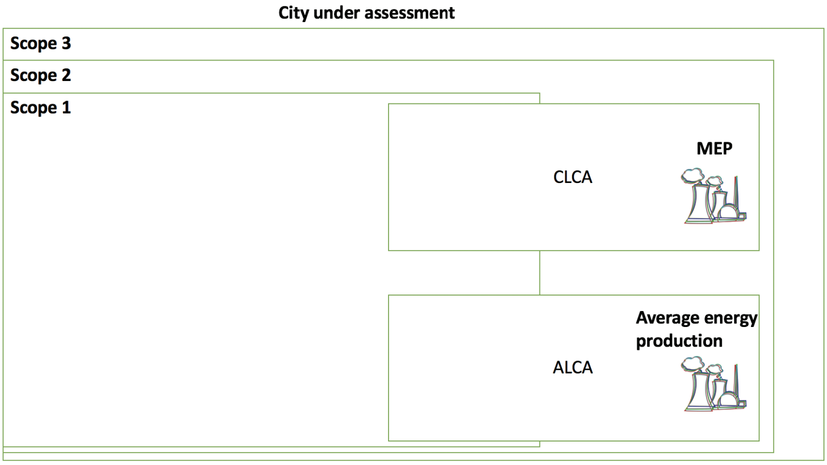


Figure 1. The relationship between MEP, ALCA, CLCA and carbon neutral cities.

1.2 Theoretical framework

Whereas for instance above mentioned GHG accounting methods propose to include consumption-based energy related scope 2 emissions into GHG accounting, scope 3 or indirect GHG emissions are still excluded which limits the outlook of the actual implications within larger boundary. Also, CLCA related consequential implications from municipal energy related actions are not included.

Like vice earlier mentioned studies by Satterthwaite (2008), Hoornweg et al. (2011), Dodman (2009) and Sovacool & Brown 2010, scope 2 and scope 3 implications from scope 2 and scope 3 has been shown remarkable in recent research in cities' GHG emission scope boundary studies.

The importance of non-state actors is presented by Muramochi et al. (2020), where scope 1 and scope 2 GHG reduction operations of such actors were identified to achieve national targets until 2030 without state or national government actors. Lui et al. (2020) presented that by global initiatives and thus scope 3 GHG reduction implications could represent some 30% of the national GHG reduction targets. Also, the importance of scope 3 has been raised by Mytton (2020) by questioning the voluntary reporting of scope 3 emissions and thus being possible to hide GHG emissions with relevant actions. From highest end Larsen & Hertwich (2009) assessed these indirect GHG emission to represent 93% of municipal services. From the industry point of view Hertwich & Wood (2018) showed that scope 3 of global industry has been growing 84% from 1995 to 2015 where scope 1 grow only 47%. The importance of scope 3 interactions within city networks have been highlighted in studies such as Chen et al (2016a) and Chen et al (2016b). More case specific literature has been presented in dissertation's research papers. Literature reviews on the research within dissertation's research area has been carried out by searching research articles on carbon neutral cities, scope and boundary studies within cities and energy systems together with LCA studies within these areas.

Research within this field has thus studied several perspectives of larger than scope 1 boundary GHG assessment, but the research within implications within scope 2 and 3 boundaries occurring from municipal actions is clearly missing. This is still even cities share in global anthropogenic GHG emissions has been presented to be 70% by IEA (2008). As current research proposes, implications from scope 2 and 3 for a city can be significant it can be argued that vice versa implications from a city to scope 2 and 3 can be significant as well. It can also be assumed that cities' role as larger than scope 1 GHG emission influencer is much higher than what initially thought and above-mentioned research together with GHG accounting methods are missing this great potential and perspective.

1.3 Research problem and research questions

Mentioned literature and described theoretical framework depicted a gap in understanding and utilization of wider boundary system implications when reaching carbon neutral cities. Municipalities as administrative organization of a city are central stakeholders when reaching carbon neutral cities and societies as they hold power over municipal infrastructure such as municipal energy systems. Where municipalities tend to focus on scope 1 GHG emissions in GHG accounting, actual implications of municipal energy actions are far more complicated and significant when widening the boundary implication assessment to scope 2 and 3 and when introducing the CLCA perspective. Thus, the cities' role concerning the GHG implications within all the scopes is much more central than it seems when limiting the boundaries into scope 1. Unfortunately, this is poorly understood and utilized in GHG reduction actions.

The aim of the dissertation is to illustrate the dynamics of GHG implications with the broadened assessment boundary of scope 2 and 3 when introducing the CLCA approach into municipal energy related GHG reduction actions. Municipal energy systems and actors represent the largest share of the overall energy system in Finland. Dissertation studies municipality level actions to decrease GHG emissions of scope 1 and consumption-based scope 2 and to develop carbon neutral city by introducing scope 2 and 3 together with a CLCA approach to demonstrate the actual implications and potential of municipal energy related actions.

The main research question of the dissertation is stated as follows:

How does widening the boundary description for GHG emissions from the GHG Protocol's Scopes 1 to Scopes 2 and 3 affect the implications of municipal energy related actions when aiming to achieve carbon neutral cities?

The reason for the research question is due to relatively unstudied area concerning the creation of carbon neutral cities and the energy system implications, more specifically, MEP and the GHG Protocol's Scopes 3 implications. The research question is formulated from the municipal actor perspective to identify what could be done in order to efficiently further the carbon neutrality of cities and societies. As the scope of the research question is wide, the dissertation more specifically addresses the role of marginal implications and allocation methods of energy, how cities could participate in reducing the consumption-based carbon footprint of individual city residents and how cities could achieve a carbon neutral city status by utilizing the widened scope to define GHG emissions and CLCA dynamics. The dissertation thus presents terms carbon footprint and GHG emissions. According to Wiedmann and Minx 2008, the carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product. GHG emissions are emissions that trap heat in the atmosphere [EPA 2020] and are aggregated with 100-year global warming potential as with IPCC 2018. In the dissertation carbon footprint is used with consumption-based carbon footprint of city residents in line with previous definition and GHG emissions is used commonly to present carbon equivalent emissions within scopes 1-3.

1.4 Roles of the research papers

This dissertation research is based on four peer reviewed research papers. All the papers introduced the use of the GHG Protocol's Scopes 2-3 boundaries and the CLCA approach to identify the nature of a particular phenomenon or implication.

1.4.1 The role of the first paper: Consequential Implications of the Municipal Energy system on the Carbon Footprint of a City Resident

The first paper assessed the general consumption-based carbon footprint of city residents and studied the actual implications of municipal energy in the city residents' carbon footprint. The purpose was to analyse the role of local municipal energy systems in the consumption-based carbon footprint of a city resident. The paper studied how energy system dynamics can change the relative significance of municipality energy production choices compared to the direct consumption-based carbon footprint evaluations currently in use.

1.4.2 The role of paper 2: Planning for a Low Carbon Future? Comparing Heat Pumps and Cogeneration as the Energy System Options for a New Residential Area

As the widened boundary changed the role of municipal energy in the first paper, the second paper studied the uncertainties related to the allocation method chosen, as well as the consequential implications within the GHG Protocol's Scope 2 concerning municipal energy and uncertainties related to indirect energy related scope 3 emissions of municipal energy when these indirect emissions are taken into account. The purpose was to compare the choice between CHP and a ground-source heat pump (HP) as the energy systems of a new residential area in the light of the uncertainty of the GHG assessment.

1.4.3 Role of the paper 3.: Uncertain Greenhouse Gas Implications in Waste Heat Utilization – A Case Study with a Data Center

As the second paper studied uncertainties related to scope 2 and 3 emissions, the third paper further studied scope 2 and scope 3 consequential implications when a city reduced its scope 1 emissions by utilizing waste heat and heat pumps in district heating. The case study assessed GHG emission implications within the GHG Protocol's Scopes 1-3, as proposed in the previous case study. The CLCA perspective was included and considered within Scope 3 assessments. The purpose was to illustrate how the utilization of waste heat to reduce municipal-bounded GHG emissions can lead to an increase in GHG emissions within wider boundaries.

1.4.4 Role of the 4. paper - Pathways to Carbon-Neutral Cities Prior to a National Policy

The fourth paper investigated how implications and potentials found in papers 1-3 are recognized in one of the central municipal carbon neutrality roadmaps. The purpose of the paper was to evaluate different options for a progressive city to reach carbon neutrality in energy prior to the surrounding system. The study focuses on the energy sector's GHG emissions.

Table 1 presents these papers together with the purposes of each paper. The table was used and updated continuously throughout the compilation part of the dissertation when discussing the research and introducing different perspectives around the research papers and completing dissertation research.

Table 1. Purposes of the research papers.

Main research Questions	How does widening the boundary description for GHG emissions from the GHG Protocol's Scopes 1 to Scopes 2 and 3 affect the implications of municipal energy related actions when aiming to achieve carbon neutral cities?			
Paper #	1	2	3	4
Title of the paper	Consequential Implications of the Municipal Energy System on the Carbon Footprint of a City Resident	Planning for La Ow Carbon Future? Comparing Heat Pumps and Cogeneration as the Energy System Options of a New Residential Area	Uncertain Greenhouse Gas Implication in Waste Heat Utilization – A Case Study with a Data Center	Pathways to Carbon-Neutral Cities Prior to a National Policy
The purpose of the research	To analyse the role of local municipal energy systems concerning the carbon footprint of a city resident.	To compare, from an urban planning perspective, the choice between CHP and a ground-source heat pump (HP) as the energy systems for a new residential area in the light of the uncertainty of the GHG assessment.	To illustrate how the utilization of waste heat to reduce municipal boundary GHG emissions may increase such emissions within wider boundaries.	The purpose of this paper was to evaluate different options for a progressive city to achieve carbon neutrality in energy prior to the surrounding system.

1.5 Structure of the dissertation

The summary part of the dissertation is divided into 4 sections, followed by the research articles. The first section has presented the background for the research, the research questions and structure of the research. The second section presents the research methodology by explaining the research approach in more detail together with the research methods. The third section presents the main findings of the dissertation. These findings are drawn from the research paper findings, which are presented in more detail in the appended research papers.

The fourth section includes the discussion and conclusions of these research findings. This section evaluates the results and proposes further research needs within the field.

2. Data and methods

The first sub-section presents the utilized research materials. The second subsection focuses on the research methods applied in the different studies.

2.1 Research materials

Dissertation research examined for case studies where Finnish cities and their GHG emission implications were used as a research object. The aim was to study GHG emission implications occurred from energy choices of a city or residential area of a city.

The research materials consisted of national and city-specific statistics, simulation results and documentation. All the case studies utilized a city or cities as a target of assessment. The first paper studied the 20 biggest cities in Finland and primarily utilized consumption-based input-output data together with energy statistics and simulations. The consumption data was based on the EE IO model of the Finnish economy. The energy statistics used in this part of the research were again the official national energy statistics. The second paper studied a new residential area in Tampere, Finland. Energy consumption simulations together with energy statistics were used as research material. An energy consumption simulation was performed based on municipal energy system specifications and energy consumption modelling. The energy statistics used were official national energy statistics. The third paper studied the city of Mäntsälä in Finland and utilized actual operational energy system data from the municipal energy system and energy statistics from official national sources. The fourth paper studied the city of Vantaa in Finland and utilized process description literature of carbon neutralization of the city together with materials from semi-structured interviews. In addition, national energy scenarios and energy statistics were utilized in order to outline the implications. Table 2 presents more detailed description of the data sources and technical details of case study systems.

Table 2. Data sources and technical system descriptions of the research papers.

Paper #	1	2	3	4
Title of the paper	Consequential Implications of the Municipal Energy System on the Carbon Footprint of a City Resident	Planning for La Ow Carbon Future? Comparing Heat Pumps and Cogeneration as the Energy System Options of a New Residential Area	Uncertain Greenhouse Gas Implication in Waste Heat Utilization – A Case Study with a Data Center	Pathways to Carbon-Neutral Cities Prior to a National Policy
Data sources	- Statistics Finland's Household Budget Survey - Total sample size of the survey is around 3500 households, of which 1661 resident in the - Finnish Energy Industries statistics	- Statistics Finland - Finnish Energy Industry statistics - Cherubini et al (2009) for scope 3 indirect emission ranges	- Statistics Finland - Finnish Energy Industry statistics - Cherubini et al (2009) for scope 3 indirect emission ranges	- City's carbon neutral roadmap documentation
Technical system description	- Largest 20 Finnish cities	- Residential area in Tampere Finland - 22000m^2 - 196 apartments - 550 residents - 1730MWh/a of heat demand - 850 MWh/a of electricity demand - CHP plant with 100% of natural gas - Grid mix: - 41% renewables - 33% nuclear - 20% fossil fuels - 6% peat	- Reduced district heating with waste heat: 100% natural gas heat only boiler - COP of heat recovery: 3.3	City with 228000 residents kt CO2 of the city in 2016: - District heating 325 - Oil-based heating 60 - Electricity-based heating 69 - Residential electricity 160 - Transportation 384 - Industry and machinery 42 - Waste disposal 35 - Agriculture 2 - Total 1078

2.2 Applied research methods

The research methods applied in the dissertation's research papers include case studies, consumption-based carbon footprinting, semi-constructed interviews, content analysis and the utilisation of an LCA approach to identify system implications. The LCA approach utilized principals from ALCA, CLCA and hybrid LCA in order to identify system implications from various municipal actions which are commonly taken to reduce GHG emissions. Different LCA principals were necessary to understand the actual system implications which can be expected (later described in this chapter). A standardized full-scale LCA was not deemed necessary as it would not have provided additional information from the scope and purpose point of view. The utilized LCA approach focussed on system implications defined by different LCA principals. The case studies provided real-life settings to demonstrate these implications. Consumption-based carbon footprinting was needed to understand the role of these implications in consumption-based accounting. Documentary content analysis and semi-constructed interviews were needed to understand how these system implications are understood from the municipal perspective. Table 3 shows the research methods and materials utilized in each research paper. Table 2 is an updated version of Table 1 where new added information is marked in bold. The research method principals are presented in Sections 2.4-2.7.

Table 3. The research papers' research methods and materials.

Main Research Questions	How does widening the boundary description for GHG emissions from the GHG Proto-col's Scopes 1 to Scopes 2 and 3 affect the implications of municipal energy related actions when aiming to achieve carbon neutral cities?			
Paper #	1	2	3	4
Title of the paper	Consequential Implications of the Municipal Energy System on the Carbon Footprint of a City Resident	Planning for La Ow Carbon Future? Comparing Heat Pumps and Cogeneration as the Energy System Options of a New Residential Area	Uncertain Greenhouse Gas Implication in Waste Heat Utilization – A Case Study with a Data Center	Pathways to Carbon-Neutral Cities Prior to a National Policy
The purpose of the research	To analyse the role of local municipal energy systems concerning the carbon footprint of a city resident.	To compare, from an urban planning perspective, the choice between CHP and a ground-source heat pump (HP) as the energy systems for a new residential area in the light of the uncertainty of the GHG assessment.	To illustrate how the utilization of waste heat to reduce municipal boundary GHG emissions may increase such emissions within wider boundaries.	The purpose of this paper was to evaluate different options for a progressive city to achieve carbon neutrality in energy prior to the surrounding system.
Research method	**-Multiple case studies** **-Consumption-based carbon foot printing**	**-Case study** **-LCA approach to identify system implications**	**-Case study** **-LCA approach to identify system implications**	**-Case study** **-Content analysis** **-Semi-structured interviews**
Research material	**-City residents' consumption data of the 20 biggest Finnish cities in 2012** **-National energy production statistics**	**-Municipal energy statistics** **-Consumption simulation and energy statistics**	**-Statistics on data center waste heat utilisation in the district heating network in the city of Mäntsälä in Finland** **-Consumption and energy statistics**	**-Process description of carbon neutralization of the city of Vantaa (the third largest in Finland) and semi-structured interviews**

2.2.1 Case study

The research's approach of this dissertation to find answers to the research questions was pragmatic. As a case study research is well suited for this purpose, the research papers utilized both single and multiple case studies to understand the nature of complex researched phenomena in real life contexts. Even though papers studied particular case settings without generalizations, their purpose was to illustrate the studied phenomena in order to be able to discuss the implications within a larger context and different case settings. Because of the complexity and numerous variables related to the research objects, the use of case studies was justified approach as also proposed by Harrison et al. [Harrison et al. 2017].

A case study approach was used to examine the studied phenomena as there may not be a clear, single set of outcomes [Yin 2009]. The data for the case settings included a mix of qualitative and quantitative evidence as presented in Table 2. Both single case studies (papers 1,3 and 4) and multiple case studies (paper 2) were utilized.

The boundaries of case studies need to be well defined [e.g. Flyvbjerg 2011, Stake 1995]. The general boundaries of all the case studies in this dissertation were defined as the city under analysis. In addition, the assessments considered energy or commodity supplies as follows:

Paper 1 utilized a multiple case study design in which the consumption-based carbon footprint of the 20 largest cities in Finland were assessed. Thus, the general boundary was a city. For the consumption of all the goods and commodities, the data was based on national economic input-output data. For the energy system implications, the boundary was national.

Although paper 2 assessed system implications for the energy choices in a new residential area within a city, the system implications were assessed within a city and thus the case study boundary from this perspective was the city of Tampere in Finland. In addition, energy system implications were assessed nationally when considering the electricity grid implications, so the energy supply boundary was set at the national level (Finland).

The case study boundary for paper 3 was the city of Mäntsälä in Finland. When the energy system implications concerning the city's current use of electricity were considered, the boundary was national.

Paper 4 studied the processes involved in achieving a carbon neutral city. The case study boundary for paper 4 was the city of Vantaa and this boundary was extended to the national level when energy production was considered.

The case studies followed the same approach in which ACLA and CLCA approaches were utilized in different case settings to identify system implications in MEP together with a broadened boundary perspective. In this way the case studies supported each other to provide an outlook on what kind of system implications within boundaries 1 – 3 may occur in the process of reducing GHG emissions and carrying out municipal actions accordingly.

2.2.2 Semi-structured interviews

Semi-structured interviews were utilized in the fourth paper which assessed how carbon neutrality was pursued in a city's carbon neutrality generation processes. Grand tour questions were utilized as proposed e.g. by Leech [Leech 2002] and Spradley [Spradley 1979] in order for interviewed carbon neutral generation process owners to be able to explain how the matter was pursued in practicality.

This qualitative research approach potentially shares the respondents‘ experiences and situations in their own words. The interviews conducted as part of this study were valuable in providing an in-depth analysis of the topic under research and provided a great deal more insight than the literature review performed prior interviews. Although the interviewees were process owners of carbon neutral generation process, this approach may not provide all the information on how large city organizations and their members are pursuing the carbon neutrality in their day to day activities.

2.2.3 Content analysis

A content analysis of municipal carbon neutrality process documentation was performed in the fourth paper prior to the interviews in order to generate an understanding of the carbon neutral generation process and to generate a written description to be used as a working platform in the interviews. A relational analysis is a form of content analysis to identify different contexts and their relationship to each other [Busch et al. 2012]. By performing a conceptual analysis, concepts related to municipal processes to achieve a carbon neutral city were quantified, their relationships were identified, and their coverage was assessed.

2.2.4 Life cycle approach

Similarly to the case study approach, the life cycle approach was central to the research throughout the dissertation research papers. Where the life cycle assessment is standardized by the ISO 14000 series of environmental management standards [ISO 2006] and other sector-specific standards, there was no need to utilize the standards in their entirety. The scope of the research was to gain an understanding of the nature of the implications of various actions, so different kinds of LCA perspectives were needed only in order to define the outcomes. These perspectives included an attributional LCA, consequential LCA and hybrid LCA approach. Table 4 summarizes which of the approaches were utilized in the research papers to answer particular research questions.

Table 4. The research papers' life cycle approaches

Paper #	1	2	3	4
Title of the paper	Consequential Implications of the Municipal Energy System on the Carbon Footprint of a City Resident	Planning for La Ow Carbon Future? Comparing Heat Pumps and Cogeneration as the Energy System Options of a New Residential Area	Uncertain Greenhouse Gas Implication in Waste Heat Utilization – A Case Study with a Data Center	Pathways to Carbon-Neutral Cities Prior to a National Policy
ALCA	Indirect scope 3 emissions	Indirect scope 3 emissions	Indirect scope 3 emissions	No LCA perspective. Carbon neutral policy assessment
CLCA	Role of marginal electricity in carbon footprint and as a potential to reduce GHG emissions within larger than scope 1 boundary	Role of marginal electricity	Role of marginal electricity	No LCA perspective. Carbon neutral policy assessment
Hybrid LCA	The share of municipal energy in city resident' carbon footprint	Indirect scope 3 emissions	Indirect scope 3 emissions	No LCA perspective. Carbon neutral policy assessment

Consequential life cycle assessment

According to the International Reference Life Cycle Data System (ILCD) handbook, a consequential life cycle model depicts the generic supply-chain as it is theoretically expected in consequence of the analysed decision. The system interacts with the markets and those changes are depicted that an additional demand for the analysed system is expected to have in a dynamic technosphere that reacts to this additional demand [JRC-IES 2010].

CLCA aims to identify the consequences that a decision in the foreground system has for other processes and systems of the economy, both in the analysed system's background system and on other systems. It models the analysed system around these consequences. The consequential life cycle model hence does not reflect the actual (or forecasted) specific or average supply-chain, but a hypothetic generic supply-chain is modelled that prognosticates market mechanisms, and potentially includes political interactions and changes in consumer behaviour [JRC-IES 2010].

A key step in consequential modelling is the identification of the marginal processes, i.e. the generic supply-chain, starting from the decision and building the process chain life cycle model around it. Some experts identify each single marginal process, others identify a combination of several of the most likely marginal processes to obtain a more robust estimate [JRC-IES 2010].

For modelling changes in an energy system, the CLCA approach is crucial as there is only a certain amount of production capacity available from different sources. A major part of these sources and resources are utilized despite increased consumption. This leads to earlier mentioned increase in the MEP.

Although no full-scale consequential life cycle assessment was carried out, the approach was utilized in part in papers 1, 2, 3, and 4. In first paper the CLCA approach was used to identify marginal system changes in the electricity system when additional capacity was required from it. In the second paper, the CLCA approach was utilized to identify system implications when municipal electricity replaced MEP within the grid. In the third paper, the CLCA approach was utilized to identify GHG emission implications when the increased electricity demand of a city increased the MEP. In the fourth paper, a CLCA approach was utilized to explain how cities could extend their GHG emission reductions by replacing MEP.

Attributional life cycle assessment

According to International Reference Life Cycle Data System (ILCD), an attributional life cycle model depicts an actual or forecasted specific or average supply-chain plus its use and the end-of-life value chain. The existing or forecasted system is embedded into a static technosphere [JRC-IES 2010].

ALCA depicts the potential environmental impacts that can be attributed to a system over its life cycle, i.e. upstream in the supply-chain and downstream following the system's use and end-of-life value chain. Attributional modelling makes use of historical, fact-based, measurable data of known (or at least knowable) uncertainty, and it includes all the processes that are identified to relevantly contribute to the system being studied [JRC-IES 2010].

In attributional modelling the system is hence modelled as it is or was (or is forecasted to be). This also applies to its background processes: as background data, producer-specific LCI data is ideally used where specific producers provide a background good or service (e.g. a single tier-two supplier might produce the required bricks for a large office building). Average or generic data is typically used where the goods and services stem from a wide mix of producers or technologies. The change from specific to average or generic data is only done for practicality reasons and is a simplification that is justified from the averaging effect that typically occurs several steps up and down the supply-chain and value chain [JRC-IES 2010].

Therefore, its utilization in case studies and to identify system implications from energy system is valuable. In practice in can be seen as a potential outcome of longer-term system implications if a system to which chances have been made would attempt to recover itself from these chances and revert back to its initial situation. For instance, when demand increases in an energy system and MEP acts accordingly, cheaper, and potentially environmentally friendly production capacity could be established accordingly within the longer-term.

Similarly to CLCA in this dissertation, no full-scale ALCA was performed, but the approach was utilized in papers 1, 2, 3 and 4. In the first paper an ALCA approach was utilized to assess the initial GHG emission levels of the case city and its district under assessment prior to added new consumption. The ALCA approach was used to assess the GHG implications of local CHP, also with increased demand. In the second paper, an ALCA approach was utilized to generate process LCA data of the municipal energy production. In the third paper, the

ALCA approach was utilized to assess system implications within the GHG Protocol's Scopes 1 and 2, and within Scope 3 when a MEP increase was not considered. In the fourth paper, an ALCA approach was the basis for all the carbon neutral scenarios and system implications when MEP was not raised as an additional.

Hybrid LCA and City residents' consumption-based carbon footprinting

The consumption-based carbon footprinting of city residents carried out in paper 1, followed an environmentally extended input–output (EE IO) analysis based on input-output economics (Leontief, 1970]. The EE IO carried out in the study followed same principals as described by Ottelin et al. (2015) and was further developed into a hybrid LCA to combine both process- and environmental-index corrected economic input-output data. Where the input-output data-based assessments lacked in accuracy, the energy use related environmental implications were based on process assessments of each case study under a multiple case study assessment.

The implications of the municipal energy use in city residents' carbon footprint is essential from the dissertation perspective because individual environmental awareness is increasing and cities can account their GHG emissions based on consumption, which means that private consumption can also be addressed. So, the capabilities of municipalities and their energy system to support the low carbon footprinting of individual city residents can be crucial.

When examining the implications of the municipal energy system in the city residents' carbon footprint, actual municipal energy system data was utilized. Process-based municipal energy system GHG implications were assessed and the EEIO-based carbon footprint was corrected using the data on the municipal energy system implications where the consumption was identified as using the municipal energy system rather than national level.

3. Results

This chapter presents the results of the dissertation. First, the main contributions from each research paper are presented from the perspectives of the dissertation's research question setup and specific sub-questions. Second, these findings are discussed, summarized and refined to answer the main research question together with specific sub-research questions.

3.1 Contributions from research paper 1

Although the primary definition of a carbon neutral city which this dissertation follows is the non-consumption-based definition by Cities C40 [Cities C40 2019], paper 1 studied the role of municipal energy systems in the consumption-based carbon footprint of city residents. The study strongly justified the research as part of the dissertation because consumption-based carbon accounting more closely represents the actual environmental burden cities incur and thus their ability to minimize these emissions from the energy system perspective is crucial to understand. In the study, a hybrid life cycle assessment approach was utilized in order to understand actual implications of local municipal energy systems from this perspective. In addition, the research paper's results can be discussed from the perspective of compensation of other GHG emissions than the stationary energy systems of the city.

Although it was initially perceived that the role of municipal energy in direct municipal energy consumption accounted for less than 20% of the city residents' carbon footprint (when locally produced and utilized energy was allocated for city residents), this share increased rapidly when different aspects were added and taken into account. When the municipal electricity production's role was allocated for city residents as a whole, the share increased to over 30%. Finally, when the role of municipal electricity production within the electricity grid and supply system was analysed, it was found that the carbon footprints of city residents would be significantly higher without municipal energy supply as the demand would have to be covered then by more GHG intensive production. Similarly, cities have the potential to make virtually all their residents' carbon footprints negative by replacing more GHG intensive marginal energy in the market and ensuring the supply of carbon free energy for their own demand. This implication happens when GHG intensive marginal production is replaced by the excess municipal energy production which has not been used to fulfil the direct demand of the city residents. Figure 2 presents the carbon footprint of city residents as presented in the second research paper and Figure 3 shows the implications of the marginal system-level emission decrease as presented in same paper. In Figure 2, excess energy is expressed in the brown separate columns and the stacked columns represent the city residents' consumption categories. In Figure 3, the implications of marginal energy replacement are presented per city.

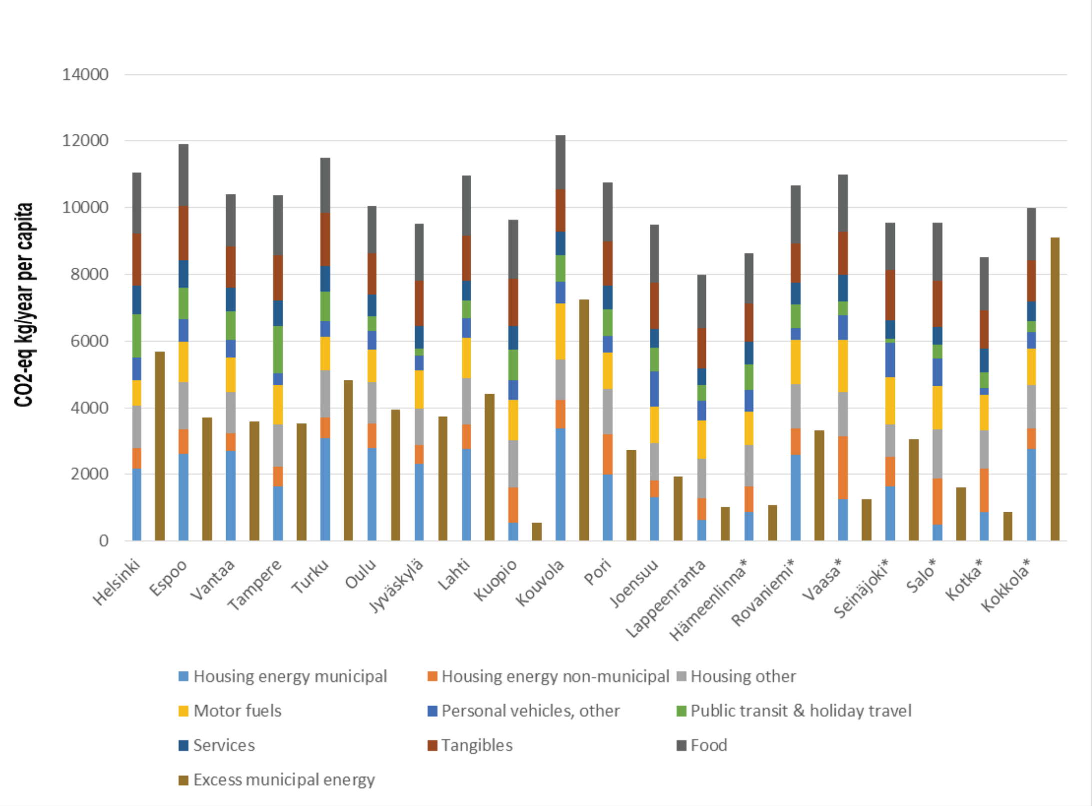


Figure 2. Carbon footprint of city residents as presented in the first research paper.

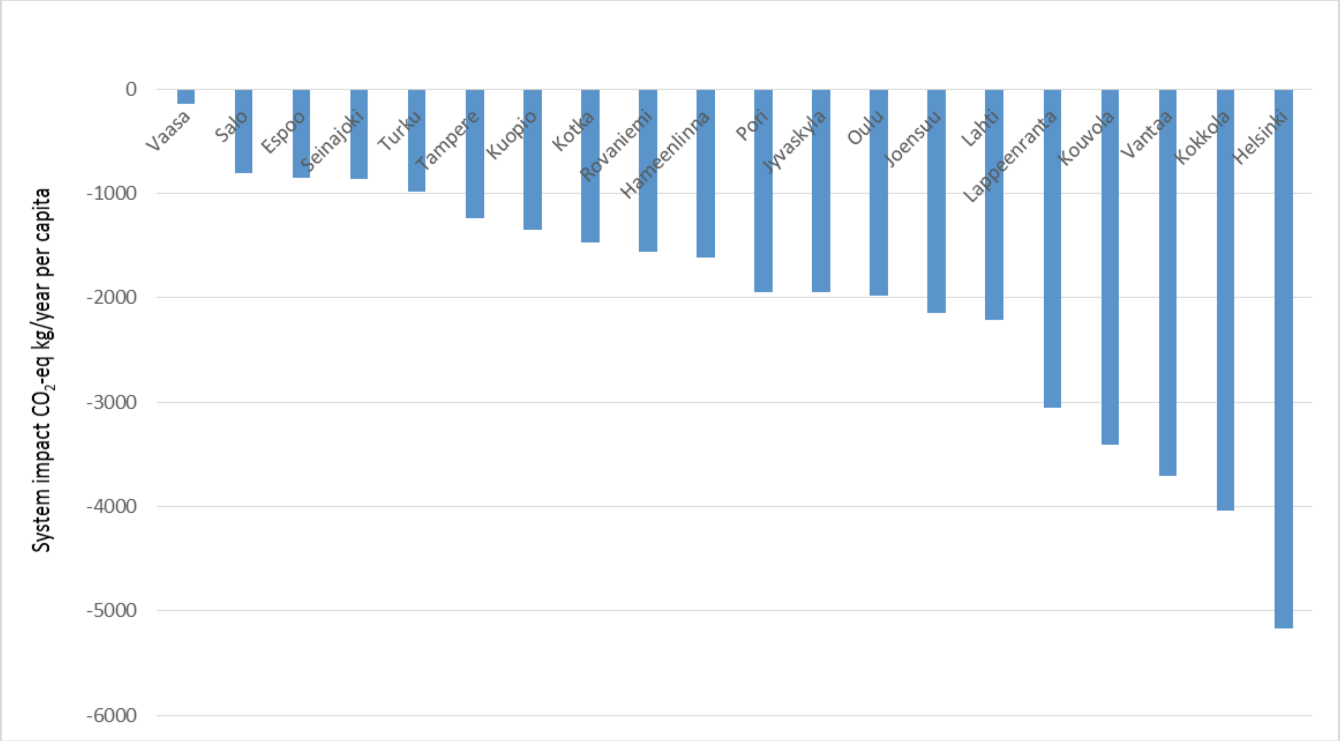


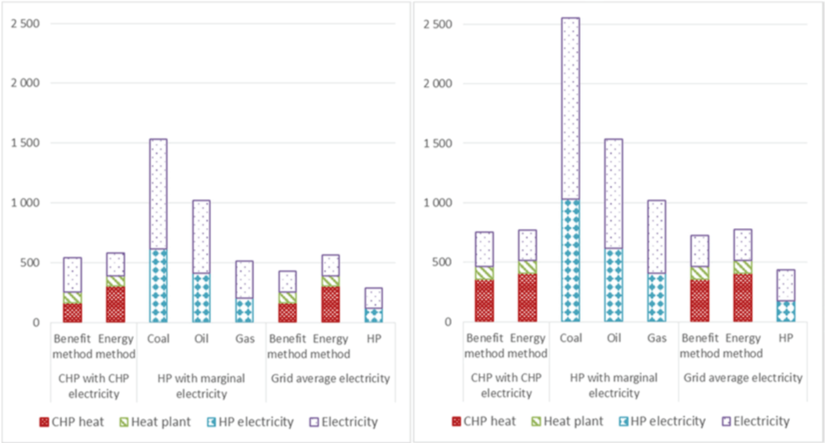
Figure 3. Implications of marginal system-level emission reductions as presented in the second research paper.

3.2 Contributions from research paper 2

Second paper studied the uncertainties in relation to municipal heating energy choices' GHG implications, the primary message was that these uncertainties can be so wide that it is impossible for cities to make a decision which would unquestionably lead to minimum levels of GHG emissions. The main reasons for this are the role and unpredicted changes in energy supply systems, uncertainties related to the actual energy sources utilized and differences between various allocation methods.

As it is impossible to identify lowest GHG emissions within the lifetime of a residential area by making a decision on which existing heat energy supply systems it would be connected to, the best possibility to achieve a low GHG emission outcome would be to ensure that the chosen energy supply system would meet the requirements of the expected upcoming GHG emission levels. This would broaden the focus of municipal actors from the initial energy supply system decision to the ongoing management of the development of the chosen energy supply system. Initially this would require ensuring that there is no technological lock down in relationship to the GHG emission development goals within the life cycle and to ensure that the development would be financially feasible. As a consequence of this approach, municipal actors should systematically ensure the development of different districts and the city as a whole where different districts are largely integrated with each other. Potentially through continuous management, increased GHG reductions from marginal energy replacement could be achieved and ensured by a city.

Figure 4 presents the comparison of different energy supply options as presented in the research paper. The paper utilized the lowest and highest possible values for the indirect life cycle emissions for different energy supply systems in order to illustrate the uncertainty ranges. In the figure below, on the left side, the lower indirect GHG emissions were assumed, while on the right side the higher GHG intensities were assumed. The electricity and heat consumption implications were simulated with CHP and ground source heat pump options, using both benefit and energy allocation methods. Where the purely oil- and gas-based heat pump-based energy supply options have significantly higher GHG emissions, they are only hypothetical because the choice of the real-life energy supply system and rest of the options were so close to each other that uncertainties make calculations of the lowest possible GHG emissions impossible.



(a) **(b)**

Figure 4. (a) The annual GHGs incurred by the Härmälänranta settlement with the lower GHG intensity boundaries (t CO2e/a); (b) The annual GHGs incurred by the Härmälänranta settlement with the upper GHG intensity boundaries (t CO2e/a).

Research paper 2 addressed the scope and allocation issues of energy the most of the research papers. It was seen that uncertainties in scope 3 and indirect GHG emissions were emphasized with fossil-based electricity and these options cannot compete with existing CHP-based system even with lowest indirect emissions if the source is something else than natural gas which is relatively low emission energy source when indirect emissions are low. These indirect and scope 3 emissions were the most results impacting factors and not the allocation method chosen as such. The importance of an allocation method is to divide the emissions between heat and electricity where the difference can be relatively high. Results also highlighted that CHP has been relatively efficient method to produce energy when grid's electricity has been relying on fossil-based sources. However, when electricity production increasingly utilized low-GHG energy sources, it is hard for it to compete without changing the energy sources as well.

3.3 Contributions from research paper 3

The third paper found that the utilization of waste heat which is commonly used to reduce a city's GHG emissions, may lead extensive increases in the amount of GHG emissions within Scopes 3 of the GHG Protocol when the consequential life cycle perspective was assessed together with marginal energy implications. For cities which only take account their Scope 1 GHG emissions, this might not be evident at all as this implication is not recognized by Scope 1 the GHG Protocol. The results emphasize the important role of the implications of marginal energy production. From another perspective, this might also be seen as an opportunity for cities to take responsible and effective actions by examining marginal system implications, which was also identified by research papers 1 and 2. By following this approach, cities could reduce the actual GHG emissions within a complete system by focusing on replace high GHG emitting energy production within the overall system. Figure 5 presents the main findings of the 3rd research paper in relationship to its contribution to the dissertation findings. In the figure the annual implications within all scope boundaries 1 - 3, together with ACLA and CLCA approaches are compared. The figure highlights the contrast between targeted (GHG Protocol Scope 1) and potential outcomes (GHG Protocol Scope 3 with the CLCA approach).

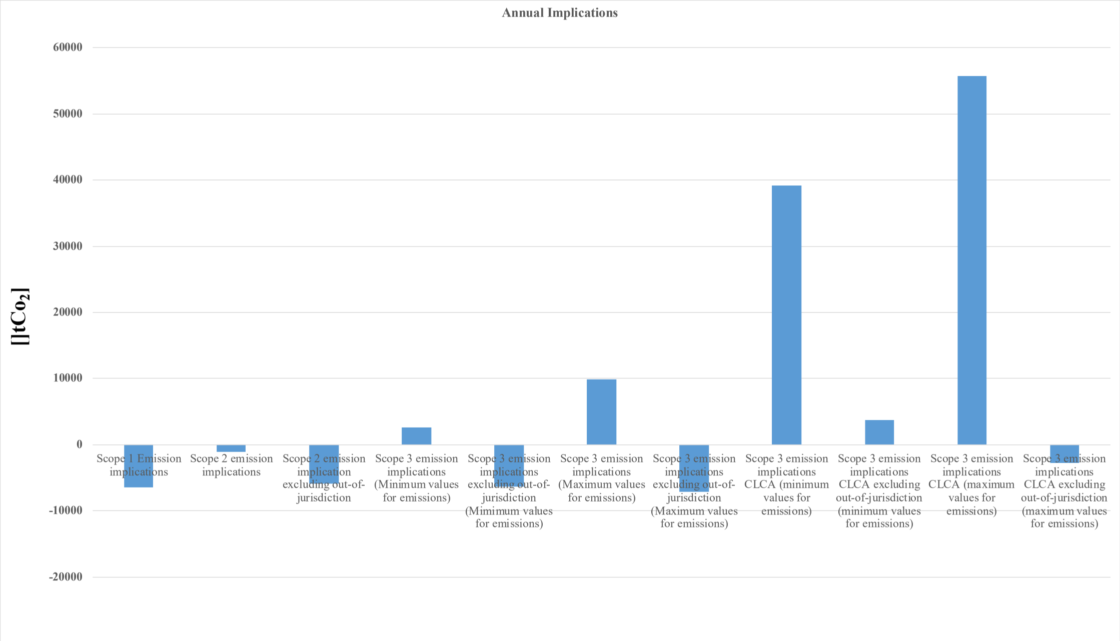


Figure 5. Annual implications within all the assessments and GHG Protocol scopes [from left to right: GHG Protocol Scope 1 emission implications, GHG Protocol Scope 2 emission implications, GHG Protocol Scope 2 emission implications excluding out-of-jurisdiction, GHG Protocol Scope 3 emission implications (minimum values for emissions), GHG Protocol Scope 3 emission implications excluding out-of-jurisdiction (minimum values for emissions), GHG Protocol Scope 3 emission implications (maximum values for emissions), GHG Protocol Scope 3 emission implications excluding out-of-jurisdiction (maximum values for emissions), GHG Protocol Scope 3 emission implications CLCA (minimum values for emissions), Scope 3 emission implications CLCA excluding out-of-jurisdiction (minimum values for emissions), Scope 3 emission implications CLCA (maximum values for emissions), and Scope 3 emission implications CLCA excluding out-of-jurisdiction (maximum values for emissions)].

3.4 Contributions from research paper 4

The fourth paper exemplified how the municipal energy systems could be seen by a city as a possible means to achieve carbon neutrality. It was identified that from the municipal energy system perspective, processes aiming to achieve a carbon neutral city included carbon removal from municipal heat supply and introducing distributed small-scale energy generation. In addition, major energy consumption reductions together with energy efficiency improvements were seen as central tools.

Still, the role and potential of large scale GHG emission free electricity production was not recognized. This was even when the city's owned energy company had a relatively large amount of GHG emission free centralized electricity production within the national boundary as shown in Table 5. If this would have been recognized, it would have reduced the GHG emission levels of the city significantly. Likewise, the potential to utilize marginal implications as described by research papers 1- 3 was not conserved by the cities. The city under assessment relied heavily on the national development of carbon free electricity production and the reduction of electricity consumption, which is present in the development assumptions in rows 3 and 4 in Table 6 which presents the carbon development scenarios of the city under assessment. These findings together with the city's carbon neutralization process, as presented in Table 7, showed that the scope 3 energy system production and system implications are not well understood by the case city. In addition, and as presented in Table 7, only direct processes to achieve carbon neutrality were set for municipal district heat production, the rest of the processes were mainly indirect and non-mandatory, limiting the city's capability to steer the process.

Table 5. Municipal energy system details as presented in the fourth paper.

Electricity Production Details		**DH Production Specifications**	
Electricity consumption total (GWh)	1913	Number of CHPs	3
Electricity consumption related GHG (kgCO$_2$ekv)	233,400	Number of boilers	6
CHP-based electricity production (GWh)	634	Net production (GWh)	1875.8
CHP-based electricity production related GHG (gCO$_2$ekv/kWh)	262	Heat delivery and losses (GWh)	152.2
Co-owned centralized electricity production (GWh)	777	Boiler conversion losses (%)	11.5
Co-owned centralized electricity production-related GHG (kgCO$_2$ekv)	0	Fuels used for heat and CHP electricity production	
Used Fuels			
Light oil (GWh)	0.4	Coal (GWh)	1199.1
Natural gas (GWh)	559.7	Municipal waste (GWh)	1057.8

Table 6. Carbon-neutral city GHG scenarios as presented in the fourth paper.

kt CO_2-ekv	1990	2016	2030 BAU	2030 CN	1990 change %
District heating	271	325	188	52	−81
Oil-based heating	74	60	48	0	−100
Electricity-based heating	60	69	52	17	−72
Residential electricity	165	160	141	45	−73
Transportation	318	384	207	97	−69
Industry and machinery	95	42	16	3	−97
Waste disposal	91	35	22	0	−100
Agriculture	3	2	2	2	−53
Total	1076	1078	674	215	−80

BAU = business as usual, CN = carbon neutral [33].

Table 7. The 4th research paper’s main table in relation to the dissertation findings.

	Required Carbon Neutrality Actions										
Required Actions	1. New buildings must be 25% more energy efficient than required by law.		2. Heated square meters per resident/worker must not increase in new buildings.	3. The share of grid-supplied electricity for non-district heating buildings must be reduced to 40%. The remaining share needs to be produced by renewable energy. Oil-based heating must be eliminated.		4. Heating demand for building stock must decrease by 3% annually.		5. Electricity consumption for non-heating purposes must be reduced by 50% per resident/worker.		6. 20% of the remaining share of electricity consumption for non-heating purposes must be covered by the cities’ own electricity production.	7. 20% of the district heating must be provided from waste- and geothermal heat, 40% from biomass, and 40% from waste combustion. Oil, coal, natural gas, peat, and plastic waste must not be combusted.
	Defined Processes and Process Owners										
Process owner for direct process concerning the action.											Municipal district heating company (Vantaan Energia).
Direct process for the action.											Vantaan Energia is increasing the utilization of renewable energy and developing waste combustion.
Process owner for indirect process for the action.			Department of Building Control.							Department of City Planning.	Real Estate Center and Environmental Center.
Indirect process for the required action.			Department of Building Control is increasingly guiding constructors on the efficient use of space.							City plan requirements supporting the production of renewable energy.	A renewable energy city assessment should be performed with the focus on geothermal and waste heat sources.
Process owner for indirect general process related to the action.	Environmental Center, Information Center for Climate Actions.	Department of City Planning.		Environmental Center, Information Center for Climate Actions.	Department of City Planning.	Environmental Center, Information Center for Climate Actions.	Department of City Planning.	Environmental Center, Information Center for Climate Actions.	Department of City Planning.		
Indirect general process related to the action.	The service provided by the Information Center for Climate Actions will be marketed, utilized and steered actively. Its performance monitoring and measuring will be developed.	Climate impacts will be assessed in all the city plans where relevant.		The service provided by the Information Center for Climate Actions will be marketed, utilized and steered actively. Its performance monitoring and measuring will be developed.	Climate impacts will be assessed in all the city plans, where relevant.	The service provided by the Information Center for Climate Actions will be marketed, utilized and steered actively. Its performance monitoring and measuring will be developed.	Climate impacts will be assessed in all city plans, where relevant.	The service provided by the Information Center for Climate Actions will be marketed, utilized and steered actively. Its performance monitoring and measuring will be developed.	Climate impacts will be assessed in all the City plans, where relevant.		

3.5 Key findings

Several overarching findings were identified answering the research question of the dissertation:

Firstly, the allocation method may lead to different outlooks on the matter and thus to unplanned outcomes in decision making.

Secondly, the role of marginal energy and the GHG reduction potential of marginal energy systems is significant and offers extended potential for cities to reduce their GHG emissions also within a scope which is larger than the GHG Protocol's Scopes 1 boundary. Recognition of such implications and their potential should be assumed to be missing from municipal organizations.

Thirdly, the initial role of cities energy systems seems to be relatively low. Still their role in national level GHG emissions is notable. Moreover, their potential due to the implications of using marginal energy systems could even lead to virtually negative carbon footprints of city residents if decreasing of the MEP would be allocated for the city and its residents. The role of municipal energy systems and actions put into them are central when cities aim to ensuring the carbon neutral cities and society.

Fourthly, examining the implications of the marginal energy system offers an extensive method for cities to take responsible actions to reduce system level GHG emissions and potentially to compensate for their city level emissions and achieve the status of a carbon neutral city.

As a conclusive finding, and in answer to the main research question "How does widening the boundary description for GHG emissions from the GHG Proto-col's Scopes 1 to Scopes 2 and 3 affect the implications of municipal energy related actions when aiming to achieve carbon neutral cities? it can be stated that it was evident that the cities' role in the GHG Protocol Scope 3 GHG emissions is significant. Even more so when marginal production implications are considered. These implications can lead to either significantly lower or higher system level GHG emission regardless even when the initial aim is to reduce GHG emissions. Examining the marginal energy system implications is a powerful method for cities to reduce their GHG emissions within the city and within wider boundaries. Examining such implications could be utilized to compensate for GHG emissions within sectors which find it more difficult to take actions to directly reduce their GHG emissions. Still the utilization and recognition of these implications together with their potential is seen to be lacking in carbon neutral city processes.

Thus, the dissertation finding is stated as follows:

Municipal energy related actions cover far more than the GHG Protocol's Scope 1 emissions and implications. The implications of the GHG reductions within the GHG Protocol's Scope 2 and 3 together with the potential to reduce GHG emissions is greater than when limiting the boundary to the GHG Protocol's Scope 1 and ALCA. Thus, it is justified for cities to broaden the focus on energy system implications and actions to include the GHG Protocol's Scope 2 and 3 with a CLCA perspective and within the expected life cycle of an action made.

Table 8 shows the contributions of each paper in relationship to the dissertation results.

Table 8. The papers' contributions to the dissertation.

Main Research Question	How does widening the boundary description for GHG emissions from the GHG Proto-col's Scopes 1 to Scopes 2 and 3 affect the implications of municipal energy related actions when aiming to achieve carbon neutral cities?			
Paper #	1	2	3	4
Title of the paper	Consequential Implications of the Municipal Energy system on City Carbon Footprints.	Planning for a Low Carbon Future? Comparing Heat Pumps and Cogeneration as the Energy System Options for a New Residential Area	Uncertain Greenhouse Gas Implications in Waste Heat Utilization – A Case Study with a Data Cente	Pathways to Carbon-Neutral Cities Prior to a National Policy
The purpose of the research	To analyse the role of local municipal energy systems concerning the carbon footprint of a city resident.	To compare, from an urban planning perspective, the choice between CHP and a ground-source heat pump (HP) as the energy systems for a new residential area in the light of the uncertainty of the GHG assessment.	To illustrate how the utilization of waste heat to reduce municipal boundary GHG emissions may increase such emissions within wider boundaries.	The purpose of this paper was to evaluate different options for a progressive city to achieve carbon neutrality in energy prior to the surrounding system.
Research method	-Multiple case studies -Consumption-based carbon foot printing	-Case study -LCA approach to identify system implications	-Case study -LCA approach to identify system implications	-Case study -Content analysis -Semi-structured interviews
Research material	-City residents' consumption data of the 20 biggest Finnish cities in 2012 -National energy production statistics.	**-Municipal energy statistics** **-Consumption simulation and energy statistics**	-Statistics on data center waste heat utilisation in the district heating network in the city of Mäntsälä in Finland -Consumption and energy statistics.	-Process description of carbon neutralization of the city of Vantaa (the third largest in Finland) and semi-structured inter-views.
The paper's contribution to the thesis findings	**It was found that in the consumption-based carbon footprint assessment, the municipal energy accounted only for 18% of the carbon footprint contribution on average. Although the contributions of municipal energy systems were shown to be somewhat limited in consumption-based carbon footprints, the consequential electricity system implications increased the importance significantly and offer a potential for radical national carbon reductions.**	**The choice of energy system is often the most important factor in the GHG emissions of a residential area and should thus have a very central role in the environmental considerations of urban planning. However, the uncertainties in assessing the emissions from CHP and alternative options related to any specific planning situation make it very difficult to give any robust guidelines for planning. Consequently, the assessments are inevitably based on strong general assumptions instead of including the local conditions, leading potentially to biased results and unwanted GHG development in the long run.**	**The utilization of waste heat to reduce municipal boundary GHG emissions may increase such emissions within wider boundaries. The case study assessed the GHG Protocol's Scopes 1-3 when waste heat generated by a data center was utilized within a municipal DH system, replacing natural gas-based heat. Although the Scope 1 GHG emissions were shown to decrease, both Scope 2 and 3 GHG emissions increased.**	**It was identified that the city has numerous indirect measures to further and steer its carbon neutrality in relationship to energy efficiency and distributed renewable energy production. Still only a few direct and mandatory measures were considered. The responsibility to achieve an absolute carbon neutral built environment is thus seen to belong to national administration and actors within larger than city system boundary. Extended potential for carbon neutrality was identified through actions within GHGProtocol's Scope 2-3.**
Dissertation findings	**Municipal energy related actions cover far more than the GHG Protocol's Scope 1 emissions and implications. The implications of the GHG reductions within the GHG Protocol's Scope 2 and 3 together with the potential to reduce GHG emissions is greater than when limiting the boundary to the GHG Protocol's Scope 1 and ALCA. Thus, it is justified for cities to broaden the focus on energy system implications and actions to include the GHG Protocol's Scope 2 and 3 with a CLCA perspective and within the expected life cycle of an action made.**			

4. Discussion and conclusions

4.1 Contribution of the dissertation

There is an urgent need to make the built environment carbon neutral and cities can adopt a key role when addressing the practical actions needed rather than just giving guidance. Cities have generally taken the task seriously as can be seen in the numerous carbon neutral roadmaps and similar municipal actions.

Cities tend to be seen as a large group of individual users from the national perspective, and carbon neutral roadmaps and municipal actions are attempting to reduce the use of energy and to eliminate municipal energy system's GHG emissions as such. Most of these efforts are seen as positive without questioning the actual outcome. This dissertation identified numerous uncertainties related to energy choices and thus influencing the actual outcomes of the municipal choice made.

Where current research [e.g. Muramochi et al. (2020), Lui et al. (2020), Mytton (2020) and Hertwich & Wood (2018)] has been focusing to implications from scope 2 and scope 3 into cities' GHG emissions, theoretical framework of the dissertation proposed and argued that such implications has to be seen also vice versa and their significance can be assumed to be considerable. Based on the dissertation research, this hypothesis seems to be justified.

Research question of the dissertation was "How does widening the boundary description for GHG emissions from the GHG Protocol's Scopes 1 to Scopes 2 and 3 affect the implications of municipal energy related actions when aiming to achieve carbon neutral cities?". Dissertation's finding answered the question by stating: "Municipal energy related actions cover far more than the GHG Protocol's Scope 1 emissions and implications. The implications of the GHG reductions within the GHG Protocol's Scope 2 and 3 together with the potential to reduce GHG emissions is greater than when limiting the boundary to the GHG Protocol's Scope 1 and ALCA. Thus, it is justified for cities to broaden the focus on energy system implications and actions to include the GHG Protocol's Scope 2 and 3 with a CLCA perspective and within the expected life cycle of an action made."

Case studies of the dissertation studied efficient methods to further carbon neutrality, reduction of consumption-based carbon footprint and carbon neutrality furthering methods with wider than scope 1 implications and actions together with CLCA perspective. Thus, findings can be further elaborated based on the research to give more comprehensive suggestions. The conclusive message for cities based on the dissertation is to focus on the most meaningful issues which define the GHG emissions of a city and to ensure the supply of GHG free energy when the consumption itself is mostly beyond the city's jurisdiction. More specifically, it was found that cities have even greater potential to reduce the GHG emissions of a society rather than cities as themselves. However, this requires the understanding of energy system implications and broadening the boundary thinking from considering the energy issues within the GHG Protocols' Scope 1 to Scope 3. In addition, current reporting methods do not include GHG implications from cities' actions. Such implications can, as showed, offer great potential. Thus, it can be suggested that extending the reporting from current methods to include as wide as consequential annual implications from cities' made actions into scope 3 in order to manage the operations. Also, this would minimize the risk of reduction of scope 1 GHG emissions and simultaneously increasing overall scope 3 GHG emissions, which is unwanted outcome and should be recognized by cities and societies as such. Although cities are still part of the surrounding global ecosystem, which partly defines the GHG emissions, this approach increases the potential to reduce GHG emissions greatly and increases the role of cities in climate mitigation actions.

4.2 Contribution of the research papers

Paper number 2 presented that these uncertainties are present when trying to identify the most optimum energy supply for heating energy demanded at the municipal district level. This leads to a situation where decisions are hard to make, and potentially the outcomes can vary greatly from the target.

Paper number 3 presented a similar situation in which the heating demand was covered by local waste heat. Even though the heat was waste, it required an electricity supply so it could be utilized within a higher temperature heat network, and thus the most important issue became the sources of alternative energy supplies. This highlights the importance of understanding the wider boundary system, even when carrying out actions which might seem to be obviously reducing GHG emissions. Generally, all increased energy demands lead to an increased utilization of resources, so the question is to where the consumption is located so that it has the minimum environmental impact and potentially where it could be used to reduce its environmental impacts.

What is common to these two case studies, is that when decisions are made statically under the current situation and current qualities of energy supply alternatives, a major part of the actual outcomes fall beyond the jurisdiction of the city. Both perspectives, municipal actions and scientific literature, usually take upcoming development into account by generating or utilizing existing scenarios and therefore following the ALCA approach. What can be proposed is that municipalities should shift the focus from merely the initial choice of the energy supply to also include the ongoing development of the energy supply chosen. This would mean that municipalities should take care of the positive development of carbon free electricity production if the supply relies on it. Similarly, if the supply relies on other energy supplies such as a heat supply, the municipalities should ensure, for instance, that there are no technological lock downs to limit the development of that particular energy supply in relation to the municipal goals. The methods needed to ensure the appropriate development vary greatly from purchasing shares in carbon free electricity production companies or funds and ensuring the growth of production capacity accordingly to controlling the municipality's own energy company accordingly. What is also often left out of the planning process is the fact which the dissertation brought up that reducing carbon emissions within city boundary can lead to increased GHG emissions within larger boundaries. Therefore, participation at the national level in large scale energy consumption units should exist in order to reduce the GHG emissions within larger that city boundaries even though it could increase a city's GHG emissions initially.

Papers 2 and 3 highlighted the importance of understand the CLCA perspective and the system implications from the use of MEP. The first paper also managed to shift the initially relatively low importance of the municipal energy system in the city residents' carbon footprint to recognised as a more significant factor. The possibility to reduce marginal energy with virtually GHG free energy supplies offers great potential for cities to take responsible and powerful measures. The second and third papers offered a new outlook for cities and scientific audiences to shift the focus away from the initial situation to include the whole life cycle of the energy supply. The first paper showed how cities can actually utilize energy systems for effective carbon compensation and offsetting.

The fourth paper studied the research area of carbon neutral cities, which is still a relatively untouched area and offered some first insights into practical carbon development processes in one of the cities committed to carbon neutral goals. Although paper offered one of the first insights in this field, the major contribution was the recognized importance of large-scale energy production and electricity production which can be utilized also as carbon compensation and for carbon offsetting by the city. The case study's city has a carbon neutral target year which is set before the national goal for achieving carbon neutrality, which increases the role of scope 2 and 3 emissions and actions made within these boundaries.

4.3 Evaluation of the research

For the research studies under the dissertation, two research approaches were utilized throughout the research. These were the LCA and case study approaches. The LCA approach was utilized to determine the nature of the implications arising from the commonly implemented actions to reduce GHG emissions.

For the case study approach, Yin [Yin 2009] states that there are four critical conditions which a case study research needs to go through in order to maximize its quality. These are construct validity, internal validity, external validity and reliability.

4.3.1 Research validity

Construct validity means identifying the correct operational measures for the concepts being studied [Yin 2009]. This dissertation research mainly utilized publicly available research material from various sources. This research material was generated by multiple parties and the generation process itself contains numerous validity checks. Where the energy related GHG emission occurs far more various and specific sources than what was presented in the research papers, papers capability to identify measures to generate absolute carbon neutral cities is missing. However, this was not the purpose of the dissertation. Rather the scope was to identify the implications of different actions taken. Thus, in order to illustrate these implications, the case settings were justified, and it was made sure that the operational measures were valid from the papers' target point of view. Great uncertainties are present when using CLCA approach, which was central approach in the dissertation. This has been presented also by Soimakallio et al. (2011), where uncertain marginal system implication in assessment of upcoming situations were illustrated. Still, as the dissertation aimed to identify the magnitude of difference between scope 1 to scope 3 and ALCA to CLCA, this was not crucial for the research validity. However, when conduction assessment for the cities in order to prepare for upcoming situations, this uncertainty is highly important to recognize. Also, it is important to highlight that CLCA based marginal system implication within case studies were considering only marginal electricity production and not marginal heat production as the heat production of the case studies were more stable from fuel supplies. However, this may not be case in all the cases and this needs to be addressed when so like vice if there is a potential that reduction in demand of a CHP based heat eliminates this production capacity completely and changes the marginal implications of a system completely.

Internal validity seeks to establish a causal relationship, whereby certain conditions are believed to lead to other conditions, as distinguished from spurious relationships [Yin 2009]. It was identified that municipal energy related actions have a causal relationship with the GHG emissions of a city and likewise within larger boundaries. Similarly, when municipalities attempt to reduce their energy related GHG emissions, it leads to energy efficiency and energy production actions. However, the research materials utilized do not support the exact assessment of causality.

External validity establishes the domain to which a study's findings can be generalized [Yin 2009]. In order to make sure of case studies' external validity, the case studies under assessments were selected to represent typical real-world situations. A pre-examination was conducted in order to identify each case's representativity as a typical case. However, when assessing energy-related system implications within structures of the built environment it is highly determined by the surrounding infrastructure and by the geographic location of the city. Generalizations can be made to some extent to closely similar markets and infrastructures. Thus, the generalization is well adjusted to Finland but of the complete research outcome only a part will be generalizable to different surrounding infrastructures.

4.3.2 Reliability

Reliability demonstrates that the procedures of the study—such as data collection procedures—can be repeated, with the same results [Yin 2009]. The reliability of the case studies of the dissertation were taken into account and every piece of source research material is well documented and available. When the research material was not available to the public, special efforts were made in order for these research material collection procedures to be presented and their findings documented. Most of the case study materials are publicly available and the study can be easily repeated.

4.4 Conclusions

The research took a strongly pragmatic approach to identify ways cities can achieve carbon neutrality and how-to further the development of a carbon neutral society by increasing their boundary thinking from including only the GHG Protocol Scope 1 to also including scopes 2 and 3 in protocol and by integrating a CLCA perspective. Together with this pragmatic approach and perspective on the key findings, it would be important and interesting to increase the understanding from several points of view. These include the consequential energy system implications as cities achieve the status of carbon neutrality, as well as understanding the consumption-based carbon neutralization potential of cities and the complete carbon neutrality potential of cities including all sectors and carbon compensation mechanisms. Based on the dissertation, great potential for cities to further carbon neutrality is behind their ability to influence on the energy system within scope 3. This mechanism can also be seen as a contribution to consumption-based carbon-footprint reduction as cities are part of larger consumption network and are dependent on national and global supply of goods and energy. Thus, cities potential for GHG reduction is global from this perspective where they can participate for instance in increasement of the capacity of low-GHG energy production. Same applies to LULUCF sector, where potential for GHG reduction actions is mainly municipal for cities, but also national and global where they can participate for instance to forestation programs. General guidance for cities from these perspectives could be to add an additional component to GHG assessment where implications from municipal actions into scope 3 are assessed from annual average CLCA perspective and to focus on most cost-efficient and reliable GHG reduction actions which are always city-specific and not necessarily actions within scope 1.

As it was pointed out by this research and by a number of other studies [e.g. Plevin et al. 2013, Earles & Halog 2011], consequential energy system implications define the actual initial GHG impacts of different actions taken within and concerning the system. Thus, it would also be important to understand these system implications as cities change the system as a consequence of actions taken towards carbon neutrality and GHG emissions reduction. While carbon neutral generation processes of cities mostly focus on making the city itself carbon neutral, system implications outside the city boundaries can be either positive or negative from the GHG emissions point of view. These system implications can occur for instance through a change in marginal energy technology or due to market price changes of particular energy sources. As the carbon neutral efforts of entire cities are large in scale, such system implications can be dramatic.

It has been presented in several studies [e.g. Satterthwaite 2008, Hoornweg et al. 2011, Dodman 2009, Sovacool & Brown 2010] that consumption-based carbon accounting often indicates a notably larger carbon footprint than production-based accounting. Similarly, this research studied only the carbon neutrality of stationary energy systems of a city and excluded other sectors which could be partly considered similar in their nature.

It is proposed that cities could widen the perspective when furthering the carbon neutrality of society from Scope 1 to Scope 3 of the GHG Protocol. This would increase the potential of cities to further their carbon neutrality greatly and steer the focus towards the most important areas of carbon neutrality within larger than city boundaries. Thus, it is important that cities should increase their knowhow co-operate with each other and at the national level. This would increase the potential of national carbon neutrality measures, by for instance optimizing the energy production and consumption at the national level.

4.5 Future research

Understanding needs to be increased on how the most effective carbon mitigation implications throughout the whole energy system could be examined and how this knowledge can be utilized to reduce consumption-based and other GHG emissions which occur from several GHG sources globally. As it is difficult to make non-municipal actions mandatory, municipal actions to reduce surrounding energy systems' GHG emissions would potentially bring save municipal GHG reduction potential even though these would not directly be linked to city's own direct energy consumption. When aiming to achieve a carbon neutral city, this might even become a mandatory compensation method to be utilized.

In addition, a more specific and comprehensive definition of carbon neutrality needs to be introduced. Accounting for different scopes of emissions for cities as well as recognition of the carbon reduction potential within all the scopes needs to be increased. The same also applies to carbon accounting accordingly.

References

Afionis, S., Sakai, M., Scott, K., Barrett, J., Gouldson, A., 2017. Consumption-based carbon accounting: does it have a future? Wiley Interdiscip. Rev.: Climate Change 8 (1), e438.

Berkhout, P.H.G.; Muskens, J.C.; W. Velthuijsen, J. Defining the rebound effect. Energy Policy 2000, 28(6-7), 425-432.

Brännlund, R.; Ghalwash, T.; Nordström, J. Increased energy efficiency and the rebound effect: Effects on consumption and emissions. Energy Economics 2007, 29(1), 1-17.

Bruckner, T.I.A.; Bashmakov, Y.; Mulugetta, H.; Chum, A.; de la Vega Navarro, J.; Edmonds, A.; Faaij, B.; Fungtammasan, A.; Garg, E.; Hertwich, D.; et al. 2014: Energy Systems. In Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Edenhofer, O.R., Pichs-Madruga, Y., Sokona, E., Farahani, S., Kadner, K., Seyboth, A., Adler, I., Baum, S., Brunner, P., Eickemeier, B., et al. Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA.

C40 Cities. Defining Carbon Neutrality for Cities & Managing Residual Emissions – Cities' Perspective & Guidance (referred 14.12.2019). Available online: https://c40-production-images.s3.amazonaws.com/researches/images/76_Carbon_neutrality_guidance_for_cities_20190422.original.pdf?1555946416 (accessed 14.12.2019).

Carol Busch, Paul S. De Maret, Teresa Flynn, Rachel Kellum, Sheri Le, Brad Meyers, Matt Saunders, Robert White, and Mike Palmquist. (1994 - 2012). Content Analysis. Writing@CSU. Colorado State University. Available at https://writing.colostate.edu/guides/guide.cfm?guideid=61.

Chen, G.; Wiedmann, T.; Wang, Y.; Hadjikakou, M. (2016a): Transnational city carbon footprint networks – Exploring carbon links between Australian and Chinese cities, Applied Energy, 184, 1082–1092.

Chen, G.; Wiedmann, T.; Hadjikakou, M.; Rowley, H. (2016b): City Carbon Footprint Networks, Energies, 9, 602.

Cherubini, F.; Birda, N.; Cowie, A.; Jungmeier, G.; Schlamadinger, B.; Woess-Gallasch, S. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. Resourc. Conserv. Recycl. 2009, 53, 434–447.

City of Berlin. Climate-Neutral Berlin 2050. Available online: https://www.berlin.de/senuvk/klimaschutz/politik/en/ziele.shtml (accessed on 12 December 2019).

City of Copenhagen. Carbon Neutral Capital. Available online: https://international.kk.dk/artikel/carbon-neutral-capital (accessed on 12 December 2019).

City of Espoo. Tavoitteena Hiilineutraali Espoo 2030. Available online: https://www.espoo.fi/fi-FI/Asuminen_ja_ymparisto/Kestava_kehitys/Ilmastotavoitteet (accessed on 17 December 2019).

City of Helsinki. Hiilineutraali Helsinki 2035 -Toimenpideohjelma. Available online: https://www.hel.fi/static/liitteet/kaupunkiymparisto/julkaisut/julkaisut/HNH-2035-toimenpideohjelma.pdf (accessed on 17 December 2019).

City of London. Zero Carbon London. Available online: https://www.london.gov.uk/what-we-do/environment/climate-change/zero-carbon-london (accessed on 12 December 2019).

City of New York. One NYC 2050. Available online: https://onenyc.cityofnewyork.us (accessed on 12 December 2019).

City of Oulu. Kasvihuonekaasupäästöt Oulussa. Available online: https://www.ouka.fi/oulu/ilmasto/kasvihuonekaasupaastot (accessed on 17 December 2019).

City of Stockholm. Strategy for a Fossil-fuel Free Stockholm by 2040. Available online: https://international.stockholm.se/globalassets/rapporter/strategy-for-a-fossil-fuel-free-stockholm-by-2040.pdf (accessed on 12 December 2019).

City of Tampere. Ympäristöpolitiikka ja Ilmastotavoitteet. Available online: https://www.tampere.fi/asuminen-ja-ymparisto/ymparisto-ja-luonto/kestava-kehitys/ymparistopolitiikka-ja-ilmastotavoitteet.html (accessed on 17 December 2019).

City of Turku. Hiilineutraali Turku. Available online: https://www.turku.fi/hiilineutraaliturku (accessed on 17 December 2019).

City of Vantaa. Hiilineutraali Vantaa 2030 (referred 17.12.2019). Available online: https://www.vantaa.fi/asuminen_ja_ymparisto/ymparistopalvelut/resurssiviisas_vantaa/vantaan_ilmastotyo (accessed 17.12.2019).

Covenant of Mayors (2020). Reporting guidelines (referred 20.3.2020). Available: https://www.covenantofmayors.eu/index.php?option=com_attachments&task=download&id=814 (accessed 20.3.2020)

Dodman, D. Blaming cities for climate change? An analysis of urban greenhouse gas emissions inventories. Environ. and Urbanization 2009, 21(1), 185–201.

Earles, J. M.; Halog, A. Consequential life cycle assessment: A review. International J. of Life Cycle Assessment 2011, 16(5), 445–453.

European Commission - Joint Research Centre - Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance. First edition March 2010. EUR 24708 EN. Luxembourg. Publications Office of the European Union; 2010

Flyvbjerg, Bent (2011). Case study. In Norman K. Denzin & Yvonna S. Lincoln (Eds.), The Sage handbook of qualitative research (4th ed., pp.301-316). Thousand Oaks, CA: Sage.

Galvin, R. Estimating broad-brush rebound effects for household energy consumption in the EU 28 countries and Norway: Some policy implications of Odyssee data. Energy Policy 2014, 73, 323–332.

GHG Protocol, Greenhouse Gas Protocol, 2014. Global Protocol for Community-Scale Greenhouse Gas Emission Inventories - an Accounting and Reporting Standard for Cities. WRI, USA.

Greening, L.A.; Greene, D.L.; Difiglio, C. Energy efficiency and consumption – the rebound effect: a survey. Energy Policy 2000, 28(6–7), 389–401.

HARRISON, Helena et al. Case Study Research: Foundations and Methodological Orientations. Forum Qualitative Sozialforschung / Forum: Qualitative Social Research, [S.l.], v. 18, n. 1, Jan. 2017. ISSN 1438-5627. Available at: <http://www.qualitative-research.net/index.php/fqs/article/view/2655/4079>. Date accessed: 03 Apr. 2020. doi:http://dx.doi.org/10.17169/fqs-18.1.2655.

Hedman, Å. Energy-efficient city planning: The role and importance of actionable regulations. 2016. ISBN 978-952-60-6622-6

Hertwich, E and Wood, R, 2018 Environmental Research Letters 13 104013

Holttinen, H.; Tuhkanen, S. The effect of wind power on CO2 abatement in the Nordic Countries. Energy Policy 2004, 32(14), 1639–1652.

Hoornweg, D.; Sugar, L.; Gomez, C.L.T. Cities and greenhouse gas emissions: Moving forward. Environ. and Urbanization 2011, 23(1), 207–227.

IEA (The International Energy Agency). World Energy Outlook 2008; OECD/IEA: Paris, France, 2008; p. 569. ISBN 978-92-64-04560-6.

IPCC, 2018: Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland, 32 pp

Laine, J.; Ottelin, J.; Heinonen, J.; Junnila, S. Consequential Implications of Municipal Energy System on City Carbon Footprints. Sustainability 2017, 9(10), 1801.

Larsen H N and Hertwich E G 2009 The case for consumption-based accounting of greenhouse gas emissions to promote local climate action Environmental Science Policy 12 791–8

Leech, B.L. Asking Questions: Techniques for Semi-structured Interviews. Political Sci. Politics 2002, 35, 665–668.

LEONTIEF, W., 1970. Environmental Repercussions and the Economic Structure: An Input-Output Approach. The review of economics and statistics, 52(3), pp. 262-271.

Swithin Lui, Takeshi Kuramochi, Sybrig Smit, Mark Roelfsema, Angel Hsu, Amy Weinfurter, Sander Chan, Thomas Hale, Hanna Fekete, Katharina Lütkehermöller, Maria Jose de Villafranca Casas, Leonardo Nascimento, Sebastian Sterl & Niklas Höhne (2021) Correcting course: the emission reduction potential of international cooperative initiatives, Climate Policy, 21:2, 232-250, DOI: 10.1080/14693062.2020.1806021

Madlener, R.; Sunak, Y. Impacts of urbanization on urban structures and energy demand: What can we learn for urban energy planning and urbanization management? Sustainable Cities and Society 2011, 1(1), 45-53. 2011.

McCarthy, R.; Yang, C. Determining marginal electricity for near-term plug-in and fuel cell vehicle demands in California: Impacts on vehicle greenhouse gas emissions. J. of Power Sources 2010, 195(7), 2099–2109.

Mytton, D. Hiding greenhouse gas emissions in the cloud. Nature Climate Change. 10, 701 (2020). https://doi.org/10.1038/s41558-020-0837-6

Nilsson, J.S.; Mårtensson, A. Municipal energy-planning and development of local energy-systems. Applied Energy 2003, 76(1–3), 179–187.

Nystedt, Å.; Sepponen, M. Development of a Concept for Ecological City Planning for St. Petersburg; Russia. In World Renewable Energy Congress-Sweden; 8–13 May; 2011; Linköping; Sweden (No. 057, pp. 3074–3081). Linköping University Electronic Press. 2011.

Olkkonen, V.; Syri, S. Spatial and temporal variations of marginal electricity generation: The case of the Finnish, Nordic, and European energy systems up to 2030. J. of Cleaner Production 2016, 126, 515–525.

Ottelin, J.; Heinonen, J.; Junnila, S. (2015): New Energy Efficient Housing Has Reduced Carbon Footprints in Outer but Not in Inner Urban Areas, Environ. Sci. Technol., 49, 9574–9583.

Park, H.; Andrews, C. City Planning and Energy Use. In: C.J. Cleveland, Ed., Encyclopedia of Energy. New York: Elsevier, pp. 317–330, 2004.

Pehnt, M.; Oeser, M.; Swider, D.J. Consequential environmental system analysis of expected offshore wind electricity production in Germany. Energy 2008, 33(5), 747–759.

Plevin, R.; Delucchi, M.; Creutzig, F. Using attributional life cycle assessment to estimate climate-change mitigation benefits misleads policy makers. J. Industrial Ecology 2013, 18, 73–83.

Publication forum. Available online: https://www.julkaisufoorumi.fi (accessed on 14 August 2020).

Satterthwaite, D. Cities' contribution to global warming: Notes on the allocation of greenhouse gas emissions. Environ. and Urbanization 2008, 20(2), 539–549.

Siitonen, S.; Tuomaala, M.; Suominen, M.; Ahtila, P. Implications of process energy efficiency improvements for primary energy consumption and CO2 emissions at the national level. Applied Energy 2010, 87(9), 2928–2937.

Soimakallio, S., Kiviluoma, J. & Saikku, L. 2011. The complexity and challenges of determining GHG (greenhouse gas) emissions from grid electricity consumption and conservation in LCA (life cycle assessment) - A methodological review. Energy, 36 (12), 6705–6713.

Sovacool, B.K.; Brown, M.A. Twelve metropolitan carbon footprints: A preliminary comparative global assessment. Energy Policy 2010, 38(9), 4856–4869.

Sperling, K.; Hvelplund, F.; Mathiesen, B.V. Centralisation and decentralisation in strategic municipal energy planning in Denmark. Energy Policy 2011, 39(3), 1338-1351.

Spradley, J.P. The Ethnographic Interview 1979; Holt, Rinehart and Winston: New York, NY, USA, 1979.

Stake, Robert E. (1995). The art of case study research. ISBN 0-8039-5766-1 Standard EN ISO 14040:2006 Environmental management. Life cycle assessment. Principles and framework (ISO 14040:2006).

Stoeglehner, G.; Niemetz, N.; Kettl, K.H. Spatial dimensions of sustainable energy systems: new visions for integrated spatial and energy planning. Energy, Sustainability and Society 2011, 1(1), 2.

Takeshi Kuramochi, Mark Roelfsema, Angel Hsu, Swithin Lui, Amy Weinfurter, Sander Chan, Thomas Hale, Andrew Clapper, Andres Chang & Niklas Höhne (2020) Beyond national climate action: the impact of region, city, and business commitments on global greenhouse gas emissions, Climate Policy, 20:3, 275-291, DOI: 10.1080/14693062.2020.1740150

Torabi Moghadam, S.; Delmastro, C.; Corgnati, S.P.; Lombardi, P. Urban energy planning procedure for sustainable development in the built environment: A review of available spatial approaches. Journal of Cleaner Production 2017, 165, 811-827.

Turner, K. Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the UK economy. Energy Economics 2009, 31(5), 648–666.

Vandevyvere, H.; Stremke, S. Urban planning for a renewable energy future: methodological challenges and opportunities from a design perspective. Sustainability 2012, 4(6), 1309–1328.

Wiedmann, T.; Minx, J. A Definition of Carbon Footprint. CC Pertsova, Ecological Economics Research Trends 2008. 2. 55-65.

Yin, Robert K. (2009). Case study research: design and methods – 4th edition. ISBN 978-1-4129-6099-1

ZIVIN, J.S.G.; KOTCHEN, M.J.; MANSUR, E.T. Spatial and temporal heterogeneity of marginal emissions: Implications for electric cars and other electricity-shifting policies. Journal of Economic Behavior & Organization 2014, 107, pp. 248-268.

Appended Publications I-IV

sustainability

MDPI

Article

Consequential Implications of Municipal Energy System on City Carbon Footprints

Jani Laine [1,*], Juudit Ottelin [1], Jukka Heinonen [2] and Seppo Junnila [1]

[1] Department, School of Engineering, Aalto University, P.O. Box 15800, 00076 AALTO, Finland; juudit.ottelin@aalto.fi (J.O.); seppo.junnila@aalto.fi (S.J.)

[2] Faculty of Civil and Environmental Engineering, University of Iceland, Hjardarhaga 2-6, 107 Reykjavík, Iceland; heinonen@hi.is

* Correspondence: jani.laine@aalto.fi; Tel.: +358-40-357-8383

Received: 25 August 2017; Accepted: 29 September 2017; Published: 5 October 2017

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.

$$F'_e = \frac{E_e}{\eta_e} \tag{1}$$

$$F'_h = \frac{E_h}{\eta_h} \tag{2}$$

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.

$$F_e = \frac{F * F'_e}{F'_e + F'_h} \tag{3}$$

$$F_h = \frac{F * F'_h}{F'_e + F'_h} \tag{4}$$

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.

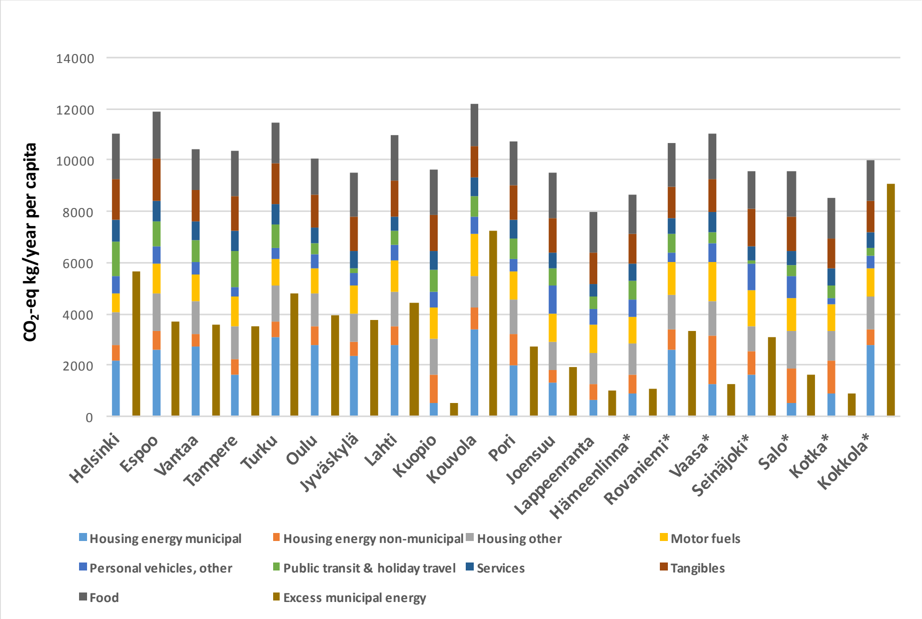


Figure 1. Reference carbon footprint model and GHG emissions of excess municipal energy. Cities with sample size below 50 households are marked with *.

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.

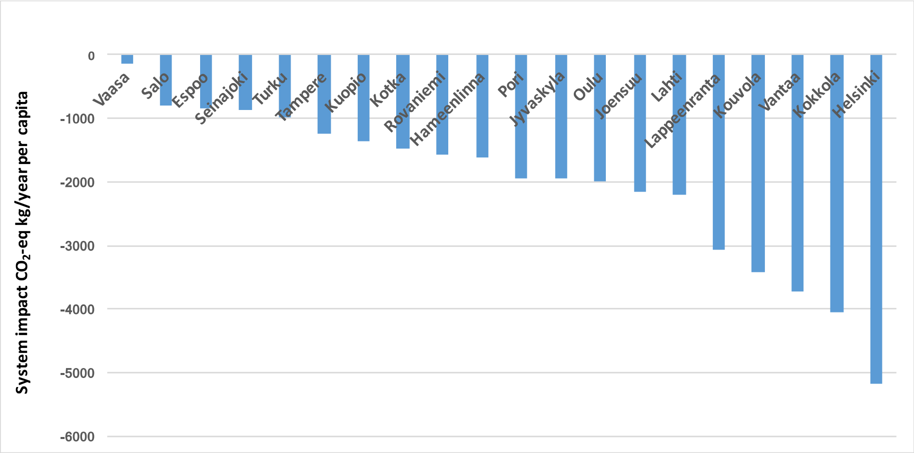


Figure 2. Initial 2012 marginal system-level emission decrease implications.

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.

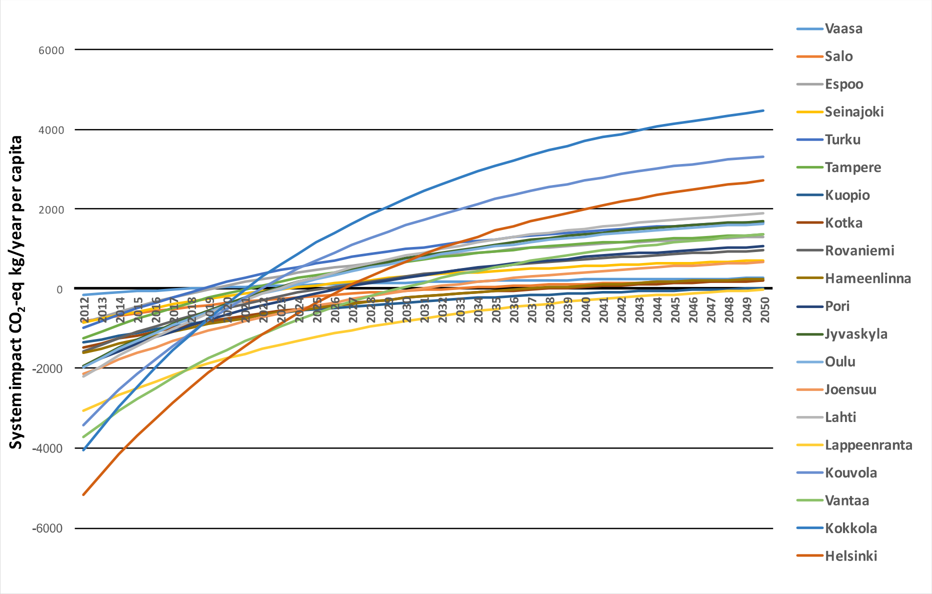


Figure 3. MEP simulation of consequential carbon footprint implications up to 2050.

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.

Acknowledgments: We thank Tekes—the Finnish Funding Agency for Innovation (Project 3000/31/15) and Marjatta ja Eino Kollin Säätiö (Grant 1102) for enabling the study.

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.

References

1. Edenhofer, O.; Pichs-Madruga, R.; Sokona, Y.; Seyboth, K.; Matschoss, P.; Kadner, S.; Zwickel, T.; Eickemeier, P.; Hansen, G.; Schlömer, S.; et al. *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*; Working Group III of the Intergovernmental Panel on Climate Change, Ed.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2011; p. 1075.
2. IEA (The International Energy Agency). *World Energy Outlook 2008*; OECD/IEA: Paris, France, 2008; p. 569.
3. Ivanova, D.; Stadler, K.; Steen-Olsen, K.; Wood, R.; Vita, G.; Tukker, A.; Hertwich, E. Environmental Impact Assessment of Household Consumption. *J. Ind. Ecol.* **2016**, *20*, 526–536. [CrossRef]

4. Seppälä, J.; Mäenpää, I.; Koskela, S.; Mattila, T.; Nissinen, A.; Katajajuuri, J.; Härmä, T.; Korhonen, M.; Saarinen, M.; Virtanen, Y. An assessment of greenhouse gas emissions and material flows caused by the Finnish economy using the ENVIMAT model. *J. Clean. Prod.* **2011**, *19*, 1833–1841. [CrossRef]
5. Wiedmann, T.O.; Chen, G.; Barrett, J. The concept of city carbon maps: A case study of Melbourne, Australia. *J. Ind. Ecol.* **2015**, *20*, 676–691. [CrossRef]
6. Fong, W.K.; Sotos, M.; Michael Doust, M.; Schultz, S.; Marques, A.; Deng-Beck, C. *Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC)*; World Resources Institute: New York, NY, USA, 2015.
7. Wiedmann, T.; Minx, J. A Definition of 'Carbon Footprint'. In *Ecological Economics Research Trends*; Pertsova, C.C., Ed.; Nova Science Publishers: Hauppauge NY, USA, 2008; Chapter 1; pp. 1–11.
8. Kyrö, R.; Heinonen, J.; Säynäjoki, A.; Junnila, S. Occupants have little influence on the overall energy consumption in district heated apartment buildings. *Energy Build.* **2011**, *43*, 3484–3490. [CrossRef]
9. Kyrö, R.; Heinonen, J.; Junnila, S. Housing managers key to reducing the greenhouse gas emissions of multi-family housing companies? A mixed method approach. *Build. Environ.* **2012**, *56*, 203–210. [CrossRef]
10. Heinonen, J.; Laine, J.; Pluuman, K.; Säynäjoki, E.; Soukka, R.; Junnila, S. Planning for a Low Carbon Future? Comparing Heat Pumps and Cogeneration as the Energy System Options for a New Residential Area. *Energies* **2015**, *8*, 9137–9154. [CrossRef]
11. Baynes, T.; Wiedmann, T. General approaches for assessing urban environmental sustainability. *Curr. Opin. Environ. Sustain.* **2012**, *4*, 458–464. [CrossRef]
12. Lenzen, M.; Pade, L.; Munksgaard, J. CO_2 multipliers in multi-region input-output models. *Econ. Syst. Res.* **2004**, *16*, 391–412. [CrossRef]
13. Druckman, A.; Jackson, T. The carbon footprint of UK households 1990–2004: A socio-economically disaggregated, quasi-multi-regional input–output model. *Ecol. Econ.* **2009**, *68*, 2066–2077. [CrossRef]
14. Heinonen, J.; Junnila, S. A carbon consumption comparison of rural and urban lifestyles. *Sustainability* **2011**, *3*, 1234–1249. [CrossRef]
15. Heinonen, J.; Junnila, S. Case study on the carbon consumption of two metropolitan cities. *Int. J. Life Cycle Assess.* **2011**, *16*, 569–579. [CrossRef]
16. Minx, J.; Baiocchi, G.; Wiedmann, T.; Barrett, J.; Creutzig, F.; Feng, K.; Förster, M.; Pichler, P.; Weisz, H.; Hubacek, K. Carbon footprints of cities and other human settlements in the UK. *Environ. Res. Lett.* **2013**, *8*, 035–039. [CrossRef]
17. Wiedenhofer, D.; Lenzen, M.; Steinberger, J.K. Energy requirements of consumption: Urban form, climatic and socio-economic factors, rebounds and their policy implications. *Energy Policy* **2013**, *63*, 696–707. [CrossRef]
18. Ala-Mantila, S.; Heinonen, J.; Junnila, S. Relationship between urbanization, direct and indirect greenhouse gas emissions, and expenditures: A multivariate analysis. *Ecol. Econ.* **2014**, *104*, 129–139. [CrossRef]
19. Jones, C.; Kammen, D.M. Spatial distribution of US household carbon footprints reveals suburbanization undermines greenhouse gas benefits of urban population density. *Environ. Sci. Technol.* **2014**, *48*, 895–902. [CrossRef] [PubMed]
20. Ottelin, J.; Heinonen, J.; Junnila, S. New Energy Efficient Housing Has Reduced Carbon Footprints in Outer but Not in Inner Urban Areas. *Environ. Sci. Technol.* **2015**, *49*, 9574–9583. [CrossRef] [PubMed]
21. Suh, S.; Lenzen, M.; Treloar, G.J.; Hondo, H.; Horvath, A.; Huppes, G.; Jolliet, O.; Klann, U.; Krewitt, W.; Moriguchi, Y. System boundary selection in life-cycle inventories using hybrid approaches. *Environ. Sci. Technol.* **2004**, *38*, 657–664. [CrossRef] [PubMed]
22. Wolfram, P.; Wiedmann, T.; Diesendorf, M. Carbon footprint scenarios for renewable electricity in Australia. *J. Clean. Prod.* **2016**, *124*, 236–245. [CrossRef]
23. Satterthwaite, D. Cities' contribution to global warming: Notes on the allocation of greenhouse gas emissions. *Environ. Urban.* **2008**, *20*, 539–549. [CrossRef]
24. Hoornweg, D.; Sugar, L.; Gomez, C.L.T. Cities and greenhouse gas emissions: Moving forward. *Environ. Urban.* **2011**, *23*, 207–227. [CrossRef]
25. Dodman, D. Blaming cities for climate change? An analysis of urban greenhouse gas emissions inventories. *Environ. Urban.* **2009**, *21*, 185–201. [CrossRef]
26. Sovacool, B.K.; Brown, M.A. Twelve metropolitan carbon footprints: A preliminary comparative global assessment. *Energy Policy* **2010**, *38*, 4856–4869. [CrossRef]

27. Sperling, K.; Hvelplund, F.; Mathiesen, B.V. Centralisation and decentralisation in strategic municipal energy planning in Denmark. *Energy Policy* **2011**, *39*, 1338–1351. [CrossRef]
28. Nilsson, J.S.; Mårtensson, A. Municipal energy-planning and development of local energy-systems. *Appl. Energy* **2003**, *76*, 179–187. [CrossRef]
29. Siler-Evans, K.; Azevedo, I.L.; Morgan, M.G. Marginal emissions factors for the US electricity system. *Environ. Sci. Technol.* **2012**, *46*, 4742–4748. [CrossRef] [PubMed]
30. Farhat, A.A.; Ugursal, V.I. Greenhouse gas emission intensity factors for marginal electricity generation in Canada. *Int. J. Energy Res.* **2010**, *34*, 1309–1327. [CrossRef]
31. Holttinen, H.; Tuhkanen, S. The effect of wind power on CO_2 abatement in the Nordic Countries. *Energy Policy* **2004**, *32*, 1639–1652. [CrossRef]
32. Siitonen, S.; Tuomaala, M.; Suominen, M.; Ahtila, P. Implications of process energy efficiency improvements for primary energy consumption and CO_2 emissions at the national level. *Appl. Energy* **2010**, *87*, 2928–2937. [CrossRef]
33. Pehnt, M.; Oeser, M.; Swider, D.J. Consequential environmental system analysis of expected offshore wind electricity production in Germany. *Energy* **2008**, *33*, 747–759. [CrossRef]
34. Mccarthy, R.; Yang, C. Determining marginal electricity for near-term plug-in and fuel cell vehicle demands in California: Impacts on vehicle greenhouse gas emissions. *J. Power Sources* **2010**, *195*, 2099–2109. [CrossRef]
35. Olkkonen, V.; Syri, S. Spatial and temporal variations of marginal electricity generation: The case of the Finnish, Nordic, and European energy systems up to 2030. *J. Clean. Prod.* **2016**, *126*, 515–525. [CrossRef]
36. Zivin, J.S.G.; Kotchen, M.J.; Mansur, E.T. Spatial and temporal heterogeneity of marginal emissions: Implications for electric cars and other electricity-shifting policies. *J. Econ. Behav. Organ.* **2014**, *107*, 248–268. [CrossRef]
37. Roux, C.; Schalbart, P.; Peuportier, B. Accounting for temporal variation of electricity production and consumption in the LCA of an energy-efficient house. *J. Clean. Prod.* **2016**, *113*, 532–540. [CrossRef]
38. Kopsakangas-Savolainen, M.; Mattinen, M.K.; Manninen, K.; Nissinen, A. Hourly-based greenhouse gas emissions of electricity—Cases demonstrating possibilities for households and companies to decrease their emissions. *J. Clean. Prod.* **2015**, *153*, 384–396. [CrossRef]
39. United Nations (UN). Classification of Individual Consumption According to Purpose (referred: 10.8.2016). Available online: http://unstats.un.org/unsd/cr/registry/regcst.asp?Cl=5 (accessed on 15 May 2016).
40. Ala-Mantila, S.; Ottelin, J.; Heinonen, J.; Junnila, S. To each their own? The greenhouse gas impacts of intra-household sharing in different urban zones. *J. Clean. Prod.* **2016**, *135*, 356–367. [CrossRef]
41. Leontief, W. Environmental Repercussions and the Economic Structure: An Input-Output Approach. *Rev. Econ. Stat.* **1970**, *52*, 262–271. [CrossRef]
42. Koskela, S.; Mäenpää, I.; Seppälä, J.; Mattila, T.; Korhonen, M. EE-IO modeling of the environmental impacts of Finnish imports using different data sources. *Ecol. Econ.* **2011**, *70*, 2341–2349. [CrossRef]
43. Motiva. Päästökertoimet 2012 (referred: 20.5.2016). Available online: http://www.motiva.fi (accessed on 20 May 2016). (In Finnish)
44. Finnish Energy Industries. Statistics 2012 (referred 26.5.2016). Available online: https://energia.fi/en/current_issues_and_material_bank/statistics (accessed on 25 May 2016).
45. Siitonen, S.; Holmberg, H. Estimating the value of energy saving in industry by different cost allocation methods. *Int. J. Energy Res.* **2012**, *36*, 324–334. [CrossRef]
46. Liikanen, J. *Allocation of Emissions in Combined Heat and Power Production*; Ministry of Trade and Industry: Helsinki, Finland, 1999.
47. Curran, M.A.; Mann, M.; Norris, G. The international workshop on electricity data for life cycle inventories. *J. Clean. Prod.* **2005**, *13*, 853–862. [CrossRef]
48. Tillman, A. Significance of decision-making for LCA methodology. *Environ. Impact Assess. Rev.* **2000**, *20*, 113–123. [CrossRef]
49. Lund, H.; Mathiesen, B.V.; Christensen, P.; Schmidt, J.H. Energy system analysis of marginal electricity supply in consequential LCA. *Int. J. Life Cycle Assess.* **2010**, *15*, 260–271. [CrossRef]
50. Mathiesen, B.V.; Münster, M.; Fruergaard, T. Uncertainties related to the identification of the marginal energy technology in consequential life cycle assessments. *J. Clean. Prod.* **2009**, *17*, 1331–1338. [CrossRef]

51. Soimakallio, S.; Kiviluoma, J.; Saikku, L. The complexity and challenges of determining GHG (greenhouse gas) emissions from grid electricity consumption and conservation in LCA (life cycle assessment)—A methodological review. *Energy* **2011**, *36*, 6705–6713. [CrossRef]
52. Rinne, S.; Syri, S. Heat pumps versus combined heat and power production as CO_2 reduction measures in Finland. *Energy* **2013**, *57*, 308–318. [CrossRef]
53. Työ- ja elinkeinoministeriö (TEM). Energia- ja ilmastotiekartta 2050—Parlamentaarisen energia- ja ilmastokomitean mietintö 16. päivänä lokakuuta 2014. Available online: http://tem.fi/documents/1410877/2628105/Energia-+ja+ilmastotiekartta+2050.pdf/1584025f-c5c7-456c-a912-aba0ee3e5052 (accessed on 20 April 2016). (In Finnish)

Energies **2015**, *8*, 9137-9154; doi:10.3390/en8099137

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

Planning for a Low Carbon Future? Comparing Heat Pumps and Cogeneration as the Energy System Options for a New Residential Area

Jukka Heinonen [1,2,*], Jani Laine [2,†], Karoliina Pluuman [2,3,†], Eeva-Sofia Säynäjoki [2], Risto Soukka [3] and Seppo Junnila [2]

[1] Faculty of Civil and Environmental Engineering, University of Iceland, Hjardarhagi 2-6, 107 Reykjavik, Iceland

[2] Department of Real Estate, Planning and Geoinformatics, Aalto University, P.O. Box 15800, 00076 Aalto, Finland; E-Mails: jani.laine@aalto.fi (J.L.); karoliina.pluuman@lut.fi (K.P.); eeva.saynajoki@aalto.fi (E.-S.S.); seppo.junnila@aalto.fi (S.J.)

[3] School of Energy Systems, Lappeenranta University of Technology, PL 20, 53851 Lappeenranta, Finland; E-Mail: risto.soukka@lut.fi

† These authors contributed equally to this work.

* Author to whom correspondence should be addressed; E-Mail: heinonen@hi.is; Tel.: +354-823-0064.

Academic Editor: Enrico Sciubba

Received: 6 March 2015 / Accepted: 20 August 2015 / Published: 27 August 2015

Abstract: The purpose of this paper is to compare, from an urban planning perspective, the choice between combined heat and power (CHP) and a ground-source heat pump (HP) as the energy systems of a new residential area in the light of the uncertainty related to the assessments. There has been a strong push globally for CHP due to its climate mitigation potential compared to separate production, and consequently it is often prioritized in planning without questioning. However, the uncertainties in assessing the emissions from CHP and alternative options in a certain planning situation make it very difficult to give robust decision guidelines. In addition, even the order of magnitude of the climate impact of a certain plan is actually difficult to assess robustly. With a case study of the new residential development of Härmälänranta in Tampere, Finland, we show how strongly the uncertainties related to (1) utilizing average or marginal electricity as the reference; (2) assigning emissions intensities for the production; and (3) allocating the emissions from CHP to heat and electricity affect the results and lead to varying decision guidelines. We also depict how a rather rarely utilized method in assigning the emissions from CHP is the most robust for planning support.

Keywords: urban planning; greenhouse gas; GHG; energy system; heat pump; cogeneration; combined heat and power; CHP; district heat; marginal production

---

1. Introduction

According to the IPCC (Intergovernmental Panel on Climate Change) (2011), energy production from fossil fuels is responsible for over 55% of the world's greenhouse gas (GHG) emissions [1]. The IEA (The International Energy Agency) (2008a) estimates that the share of energy consumed in cities accounts for over 70% of these emissions [2]. Moreover, cities form an even more important arena for climate change mitigation efforts given that city administrations have a unique ability to communicate with the public and respond to public demands quickly and efficiently and thus to bring about meaningful changes at a local level in response to global issues such as climate change [3].

Urban planning is a key channel for the municipal energy efficiency and climate action [4]. Compact urban form is predominantly seen as a prerequisite for urban environmental sustainability [5,6] further increasing the importance of the development of urban settlements. Consequently, further urbanization and densification of existing urban structures have become key planning strategies because of their connection to reduced energy requirements for housing and transportation (e.g., [7,8]). The greater density of urban structures also enables combined heat and power (CHP) production and district heating (DH), which are seen as promising means to reduce the energy systems related GHGs around the globe [9,10]. CHP can potentially decrease the fuel requirements by one third compared to separate production with an equal fuel-mix [11–13].

The global role of CHP is also expected to increase radically in the near future. In 2007, the G8 countries unanimously urged a radical increase in global CHP production [9] and the process is being implemented. For example, the CHP share is estimated to increase from the current 2015 levels of below 20% in China and in Germany to 30% in 2030, to 18% from the current 13% in the US, and to 16% from the current 9% in France [9]. Germany has even set itself an official technology penetration target to increase the share of power production by CHP to 25% in 2020 [14].

However, the environmental justification for the dominance of densification and CHP-centered policies has also been questioned, and alternative approaches to urban sustainability suggested [15–18]. Therefore, comparing the environmental benefits of CHP and other energy system options is becoming a topical issue in urban planning.

Actually, under the typical conditions of local DH networks in CHP environments and wider scale electricity grids, a number of significant uncertainties hinder verifying the environmental rationale of the decisions on energy systems and comparisons between CHP and other options. First, the choice of utilizing average or marginal technology in an assessment for electricity is often not clear, while the impact on the assessment results can be huge (e.g., [19]) as marginal technologies tend to be the most polluting. Marginal technology refers to the last generator that produces electricity to the network and the marginal electricity mix is defined as the last set of power plants that provides electricity to the network [20]. It has also been suggested that marginal production should refer to a number of technologies instead of one [21,22].

Secondly, a life cycle perspective to the emissions intensities of different energy options adds an important angle to the complexity due to the high variation in the published results (e.g., [23]). The uncertainties found in life cycle assessments (LCA) of energy production are actually one of the main problems in LCAs [24]. Furthermore, the two basic LCA approaches, attributional LCA (ALCA) and consequential LCA (CLCA), can lead to very different outcomes, but it can be very unclear which approach to utilize. The selection of approach also relates to the marginal *vs.* average production question. ALCA can be defined as a method to describe a system as it is and CLCA as a method to assess how a system will change due a certain decision (e.g., [25]). It has been said that in ALCA average technologies should be utilized, whereas CLCA refers to the situation of marginal technologies (e.g., [25,26]). Plevin *et al.* (2013) go as far as to state that ALCA should not be used when policy guidelines are searched for or the LCA results facilitate decision making [26], but there is no consensus on the question among the scientific community. The boundaries used define both marginal and average technologies and this also causes variation in studies together with the use of different LCA approaches.

Nevertheless, defining when a marginal change in demand actually occurs in the context of urban development is a complex task. As to residential energy use, new residential developments increase the demand from a local perspective, but when the boundary is extended to cover the whole system the local increase appears predominantly only as a change in the geography of demand as households move to the new location. However, any change in the geography of demand, change in temporal demand or change in quantity will have an impact on marginal power production dynamics on a system level. Since the environmental intentions in urban planning are no longer limited to the local environmental quality but include the contribution to global issues such as climate change, local optimization does not necessarily serve far-reaching planning purposes. While one option may seem to be preferable within a restricted area, from a wider perspective the situation can appear as very different. Therefore choosing the right assessment method is not trivial at all.

When extending the assessment boundary to a system level covering potentially multiple nations and sub-energy systems with their supply chain properties, defining the marginal power technologies and impacts becomes virtually impossible. If electricity imports are allowed to balance supply and demand, the definition of marginal production technologies based on the technological qualities loses its basis. For example, extensive construction of wind power capacity may cause excess energy production [27], and one way to balance the supply and demand is exports. Furthermore, the other Nordic countries in the Nordic grid are net exporters of electricity while Finland is a net importer [28]. In addition, a temporal perspective to an assessment increases the complexity due to such variables as the capacity to increase renewables. In addition, even if ALCA offered relatively simple analysis options, the uncertainties of basing decision making on CLCA remain substantial. From the perspective of increasing renewable capacity, several authors have pointed out how the periodicity of both wind and solar causes problems [29–31], but there are conflicting results as to how much this actually influences the GHG emissions [30,31]. In any case, in the future, marginal power production technologies will likely be much closer to average production technologies from the perspective of GHG emissions. This leads to a situation where CLCA cannot be used based on current system dynamics as is, although it can outrank the ALCA approach. An adequate CLCA in this context needs to predict the development of a system within the use lifetime and/or has sensitivity and probability analyses integrated into it.

The third main problem in comparing the GHGs from CHP and other options in urban planning decision making arises from the fact that there is no unequivocal method to assign the emissions for electricity and heat in CHP production (e.g., [32]). Each one can be claimed as the primary product which should carry the main emissions load. Consequentially, a number of allocation methods have been suggested with highly varying emissions distributions. Thus, a certain CHP utility operating with purely fossil fuels can still claim to be selling very low-carbon energy. If the utility chooses to allocate the emissions mostly to electricity, which is sold to the grid with virtually no impact on the grid average, it can claim to be selling low-carbon energy due to the heat production having a low carbon content, and the electricity sold to the end-user being purchased from the grid with low average emissions. An increasing share of CHP has also been shown to relate to high variability in energy GHG assessments [33].

Under the typical CHP conditions of local CHP production and a national or even international electricity grid the one conducting an assessment or introducing a policy guideline often has the power to present the emissions in the best light for the occasion, or, as happens quite often, needs to rely on second-hand information without proper transparency. However, in the studies with an urban planning perspective, the uncertainties related to the emissions from energy production are rarely given much consideration. Therefore, the results and the policy guidelines that arise can actually rely heavily on methodological choices, but these choices may not be transparent or not even recognized at all.

The purpose of this paper is to compare, from an urban planning perspective, the choice between CHP and a ground-source heat pump (HP) as the energy systems of a new residential area in the light of the uncertainty of the GHG assessment outcomes imposed by the above-mentioned factors. In the paper we present an analysis of the GHG impact of an actual new residential development in Finland to demonstrate the complexity of such an assessment and the problems in giving robust policy guidelines for planners. With the results we show that, with different but justifiable assessment choices, a very wide array of results can be obtained leading to different planning guidelines. We also discuss the comparability of CHP and HP with different assessment assumptions. The boundary issue together with ALCA *vs.* CLCA is covered by comparing both average and marginal electricity with three different choices of marginal fuel.

Finland provides an interesting case for analyzing the GHG impacts of CHP penetration and comparing CHP with other energy systems. CHP already dominates the heat supply in cities [28], and high climate mitigation aspirations have been placed on urban densification policies and further CHP utilization. It has been proposed that CHP results in environmental benefits in comparison to HPs in Finnish conditions (e.g., [34]), but opinions favoring HPs have been presented as well, and there is a current debate on which of the two is in fact superior. The issue is very complex due to the fact that currently heat production in Finland relies heavily on fossil fuels [28], which leads to significant GHG emissions in absolute terms despite the benefits of CHP. At the same time, electricity in Finland is not very GHG intensive due to the high proportion of nuclear power and renewables [28]. Finland also belongs to the Nordic grid, which enjoys even lower average emissions due to the hydropower supply from Sweden and Norway. On the other hand, the current marginal production technologies are relatively GHG intensive.

The study design is introduced in Section 2. The results of the study are presented and discussed in Sections 3 and 4 gives the main conclusions.

2. Study Design

2.1. Case Setting

This paper revisits and reanalyzes the case study of Ristimäki *et al.* (2013) [35] from the perspective of the GHGs from residential energy consumption. In their study Ristimäki *et al.* suggested that HPs would be preferable over the current CHP system from the perspectives of both the GHG and cost. However, they only used certain fixed emissions intensities and one allocation method to calculate CHP. In this paper, we reanalyzed the same case to evaluate the potential constraints and uncertainties in their study, and to see if certain assumptions would lead to the reverse selection criteria between HPs and CHP as suggested recently by Rinne and Syri (2013) [34] in a more general setting in the Finnish context.

The case area is the first phase of the new residential area of Härmälänranta in Tampere, Finland. The site is situated 5 km southwest from the Tampere city center and consists of 7 similar multi-story modern low-energy residential buildings. Every building has 6 floors, 28 apartments and 3100 m^2, totaling overall approximately 22,000 gross m^2 for around 550 residents.

The buildings of Härmälänranta fall into energy class A in Finland. The energy requirements estimated by Ristimäki *et al.* came to 80 $kWh/m^2/a$ for heating and hot water and 14 $kWh/m^2/a$ for communal building electricity [35]. For our study, we added 25 $kWh/m^2/a$ for household electricity based on the statistics of new district heated apartment buildings in Finland [36], for a total of approximately 2600 MWh/a for the whole case area.

The local energy company in Tampere is Tampereen Sähkölaitos Oy, which produces both heat and electricity. In the base year of the study, 2012, almost 80% of heat and 93% of electricity were produced in three CHP plants. Almost 70% of the delivered district heat was produced by natural gas in 2012. Other fuels used were peat (13%), wood (17%) and oil (2.5%). In the study we assumed the nearest CHP plant, Naistenlahti 1, to supply the heat in CHP options. In Naistenlahti 1 only natural gas was used as a fuel in the reference year. In the future the plan of the city of Tampere is to increase the use of renewables in energy production, first to 38% in 2020 and further to 80% by 2040. In CHP plants biogas can potentially be used instead of natural gas and solid biomass can be introduced into the DH network as well. Development scenarios from the perspective of DH and electricity from the grid were excluded from the study, but a discussion of the impacts of the 38% biomass future scenario is included as it represents the most likely near future change in the local production environment.

In 2012, the Finnish electricity production fuel-mix consisted of 41% renewables, 20% fossil fuels (50% coal and 50% natural gas), 33% nuclear power and 6% peat [37]. 25% of the electricity came from CHP [37]. The shares fluctuate annually due to variations in the global fuel prices and in renewables production, especially due to variable weather conditions. The key case data are presented in Table 1.

Table 1. Case Härmälänranta key numbers.

Categories		Values
Härmälänranta residential area		
-	Distance from Tampere city center (km)	5
-	DH network in close proximity	yes
-	Space (gross m^2)	22,000
-	Apartments	196
-	Estimated number of residents	550
Energy consumption estimations		
-	Heat and hot water (MWh/a)	1730
-	Electricity (MWh/a)	850
Naistenlahti 1 power plant		
-	Natural gas	100%
Finnish electricity grid mix		
-	Renewables	41%
-	Nuclear power	33%
-	Fossil fuels	20%
-	Peat	6%

Finland also belongs to the Nord Pool Spot electricity market along with the other Nordic countries, Estonia and Lithuania. The Nord Pool grid is further connected to the Russian, Polish and German grids. The production profile in the Nordic countries connected to the Nord Pool Spot market is based on significantly more renewables than is Finnish electricity production. In 2012, hydropower accounted for 59%, wind for 7%, geothermal power for 1%, nuclear for 13% and thermal power for 20% [14].

2.2. Compared Energy Options

We compared the two actual planning phase energy system options of Härmälänranta:

(1) CHP and
(2) HP.

We tested how the assumption on average or marginal production affects the results when different CHP allocation methods and LCA assumptions are utilized. The heating options were adopted from Ristimäki *et al.* [35], but also represented a current lively discussion topic in Finland. We utilized three different fuels for marginal production, coal, oil and gas (following Kara *et al.* 2008) [38] to give scope to the variation of the marginal mix as it should not be considered as relying on only one fuel. The marginal technology was assumed as condensing power with an efficiency range from 33% to 59% according to Cherubini *et al.* [23]. There is also potential temporal variation, especially over a longer time-span, in which fuel fills the final marginal demand change, although coal is dominant at the moment in Finland. Thus, an analysis with these three options provides a good overview of the impact of changes in marginal fuel use and of taking marginal production as a mix of fuels (and technologies) rather than simply as the most GHG intensive coal condensation, which is the prevailing tradition in Finland. Table 2 presents the compared options.

Table 2. Compared energy options.

Option	***CHP with CHP Electricity***		***HP with Marginal Electricity***			***Grid Average Electricity***		
Allocation/ fuel	Benefit Method	Energy Method	Coal	Oil	Gas	Benefit Method	Energy Method	HP
Description	CHP heat is used and the resulting electricity production is allocated to the settlement up to their electricity demand.		Coal as a marginal fuel providing all the electricity needed.	Oil as a marginal fuel providing all the electricity needed.	Gas as a marginal fuel providing all the electricity needed.	CHP heat is used but electricity is assumed to come from the Finnish grid.		HP provides heat operating with grid average electricity. Housing electricity is also grid average.

CHP is assumed to have a production efficiency range of 80% to 95% (HHV; higher heating value) following Cherubini *et al.* [23], of which 30%–45% is electricity and 50% heat. Transmission losses are excluded and are expected to be equal between electricity and heat. We also assumed 60% of the peak power demand to be produced by the CHP plant and the rest in a peak heating plant, resulting in approximately 20% of the DH demand to come from heating plants. For the heating plants we utilized an efficiency range of 77% to 91% from Cherubini *et al.* [23]. In the assessment the CHP fuel-mix is 100% natural gas, and the peak heating plant is assumed to operate with natural gas as well.

The "CHP with CHP electricity"-option is not very often included in any assessments, but we see it as a very relevant option due to the fact that the increase in the heat demand also drives increased electricity production. Commonly heat production from a CHP plant enables and drives the electricity production of such a plant, but not the other way around. As the heat demand of a site has a subsequent impact on the electricity production of the CHP plant involved, the electricity should as well be allocated to the site responsible for the increased production, at least up to the demand level. Furthermore, later in the paper we discuss the very general phenomenon that with certain CHP allocation methods a utility can claim to sell both very low carbon heat and very low carbon electricity even though it actually operates with fossil fuels with relatively high carbon contents.

Assessing the electricity demand of the CHP areas with CHP electricity enables depicting better the full subsequent impact of the new development. In our case, the subsequent change in the local CHP plant's electricity output is relatively close to the site's annual demand. Although the match is weaker if the daily and seasonal fluctuations were taken into account, this option depicts an important perspective. If there were surplus electricity from the residential area and CHP, it would decrease the marginal electricity production of the system and thus would have a reduction impact on the emissions from the current system. If the development of electricity and marginal technology production were to lead to marginal electricity production with lower emissions than the surplus electricity from the CHP, emissions would naturally increase. Ultimately the case is about subsequent displacement of resources and a precise assessment of the GHG impact of the new settlement would be very complex. Notwithstanding, the suggested "CHP with CHP electricity" option allows for assessing the GHGs when the grid impact is unknown. It is also worth noting that the "CHP with CHP electricity" option can be justified as today the plants are driven by the level of demand for heat. If there were true excess heat available from, for instance, a power plant driven by the demand for electricity, the allocation option would not be relevant.

Regarding the HP options, the efficiency measure of HPs, COP (Coefficient of Performance), *i.e.*, the ratio of produced heat to required electricity to run the pump, is typically 2.6–3.6 [39], and here we used 3.0, following Ristimäki *et al.* [35]. COP can actually reach a level of over 4.0 (e.g., [34,40]), and we discuss the impact of the COP assumption on the results as well. HPs are typically not fitted to provide 100% of the needed heat due to decreasing overall efficiency, and at least during peak hours electric heating resistors are used as complementary heaters [41], but the COP figure takes this into account.

2.3. Life Cycle GHG Intensities for Different Fuels

The published GHG intensities for different fuels and production modes vary significantly depending on the source, for example because of the assessment boundary definition and several necessary assumptions (e.g., [23,25]). Cherubini *et al.* (2009) [23] present ranges based on published LCAs for different fuels and production modes for electricity and cogeneration, which we employed in our study. The ranges do not necessarily present the highest or the lowest values suggested by earlier studies, but a wide enough spread to have a significant impact on the results and thus demonstrate the importance of the intensity assumptions. The intensities are for the output, thus including also the conversion efficiency as an important factor. Table 3 presents the figures from Cherubini *et al.* [23] employed in this study.

Table 3. GHG intensities for certain electricity and cogeneration technologies and fuels from Cherubini *et al.* (2009) [23].

Fuel/Production Mode	g CO_2e/kWh
Biomass	54…108
Biogas	54…234
Wind	3.6…36
Geothermal	7.2…36
Hydro	1.8…36
Solar	54…144
Coal	1080…1800
Oil	720…1080
Nuclear	18…108
Natural gas	360…720

Using the production distribution of the Finnish grid (see Section 2.1.) and the lower and upper values of Table 3 for calculating, the Finnish electricity production intensity has a lower boundary of 213 g CO_2e/kWh and an upper boundary of 391 g CO_2e/kWh.

For the CHP gas power plant the intensity boundaries are the range for natural gas, and for marginal production we used the ranges for coal, oil and natural gas in Table 3. For the separate heat production in peak heating plants we used the range of 252…306 g CO_2e/kWh for natural gas retrieved from the same study of Cherubini *et al.* (2009) [23] for separate heat production. Other fuels could be used as well to fulfill the peak heat demand, but the impact of separate production in our case is low.

2.4. Emissions Allocation Methods in Co-Production

There are a number of different calculation methods for allocating CHP plant emissions. These include the benefit method, energy method, the energy method, all-for-heat/electricity method, product price method, EN 15316-4-5: 2007 standard's method, ratio method, and work method. Different methods can lead to very different outcomes with important impacts on the assessment results.

In this study, the two most relevant methods were used in the calculations to allow comparisons between them:

(1) benefit method as the dominant method used in Finland and
(2) energy method as the globally most widely used method.

In addition, the all-for-electricity method was used to demonstrate an extreme case possible with the different allocation methods.

In the benefit method the emissions of a CHP plant are divided according to the ratio of fuel consumption of separate production forms. For electricity the alternative production form is a condensing power plant (efficiency 33%–59%) and for a thermal water boiler (efficiency 77%–91%). Efficiency ranges, according Cherubini *et al.* (2009) [23] representing true alternative conversion efficiencies, were utilized in the minimum and maximum calculations. Consequently, in this method, the weighting is based on the efficiencies of the separate energy productions of heat and electricity, and it makes a good comparison of the combined production's benefits if heat and electricity are produced separately. 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 cogeneration by the efficiency of the separate production of energy form.

$$\boldsymbol{F'_e = \frac{E_e}{\eta_e}} \tag{1}$$

$$\boldsymbol{F'_h = \frac{E_h}{\eta_h}} \tag{2}$$

where

F'_e = fuel consumption of alternative acquisition form for electricity
F'_h = fuel consumption of 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 (33%–59%)
η_h = efficiency of separate production of heat (77%–91%)

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 fraction with the separate production forms.

$$\boldsymbol{F_e = F\frac{F'_e}{F'_e + F'_h}} \tag{3}$$

$$F_h = F\frac{F'_h}{F'_e + F'_h} \tag{4}$$

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

In the energy method, the emissions are divided according to the ratio of produced final energy fractions. This method addresses extra emissions of heat in comparison with separate production, because the efficiency of separate heat production is higher than the efficiency in cogeneration. The division of emissions is calculated by dividing the fuel consumption of energy by the total fuel consumption and multiplying by the fuel consumption of cogeneration.

$$F_e = F\frac{E_e}{E_e + E_h} \tag{5}$$

$$F_h = F\frac{E_h}{E_e + E_h} \tag{6}$$

In the all-for-electricity method fuels are primarily subjected to electricity. Primary energy demand for electricity is calculated given the assumption that the electricity is generated via separate condensing power production. The fuel consumption of alternative electricity production is calculated by dividing the produced electricity in cogeneration by the efficiency of the separate production of electricity.

$$F_e = \frac{E_e}{\eta_e} \tag{7}$$

The primary energy allocated to heat is calculated by the difference between the total primary energy used for CHP and the primary energy allocated to electricity.

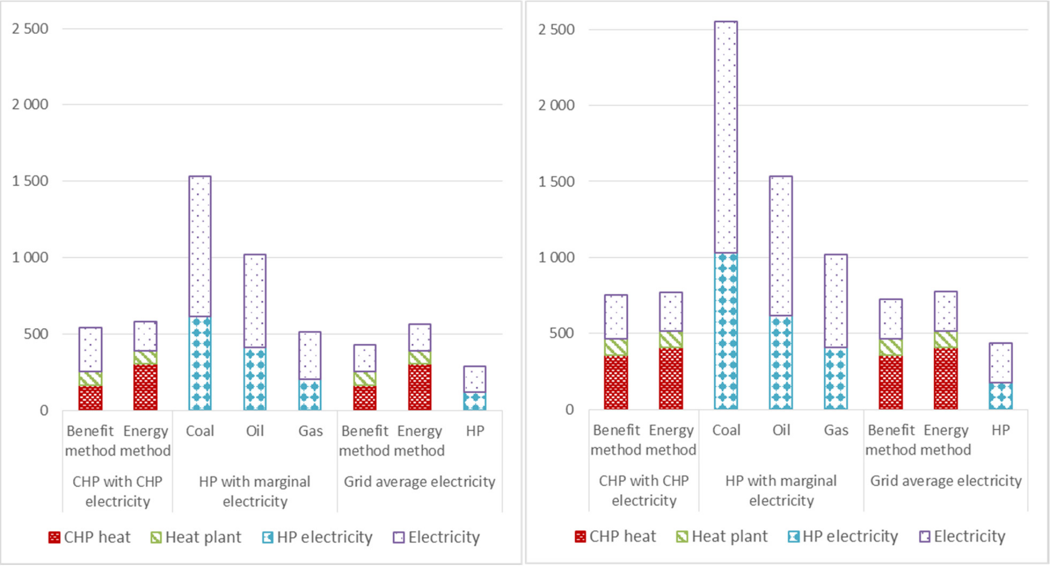
$$F_h = F - F_e \tag{8}$$

3. Results and Discussion

3.1. Assessment Results of Härmälänranta

With different assessment choices and assumptions the annual GHG impact of the Härmälänranta settlement fall into a range of 290 t CO_2e/a to 2530 t CO_2e/a, the assessment thus entailing a huge uncertainty. Furthermore, both the highest and the lowest are HP options with different LCA and electricity production assumptions. In between the extremes, CHP options vary less but still significantly enough to affect any decision guidelines. The results thus depict very clearly how difficult the energy assessment situation is from the perspective of urban planning.

In Figure 1a the results of the different options are presented according to the lower GHG intensity boundaries (see Section 2.4.). Figure 1b presents the results according to the higher boundaries. The policy guideline seems therefore to be that HP should be favored if the average grid electricity assumption is utilized, but if marginal production is assumed, HP is a better option only if marginal production is assumed to consist of a mix including a significant share of natural gas based condensation power with high conversion efficiency (or imported low-intensity electricity). In the following subsections, the main issues are discussed, which hinder robust policy guidelines regarding energy system choices in urban planning.



(**a**) (**b**)

Figure 1. (**a**) The annual GHGs incurred by the Härmälänranta settlement with the lower GHG intensity boundaries (t CO_2e/a); (**b**) The annual GHGs incurred by the Härmälänranta settlement with the upper GHG intensity boundaries (t CO_2e/a).

3.2. Interpretation of Results and Discussion

3.2.1. Average and Marginal Electricity

First, and perhaps most importantly, the very uncertain assumption about utilizing marginal or average electricity in the assessment can turn the results upside down. Especially with flexible smart electricity grids in the future and electricity trade filling the demand peaks, average grid electricity can be a justified option in an assessment like this. However, these are predictions rather than facts, and thus it is of importance to understand the uncertainties when decisions are made.

As depicted in Figure 1a,b, HP with average electricity is the best option, varying between 290 t CO_2e/a and 440 t CO_2e/a for the Härmälänranta area depending on the GHG intensities. Even with the benefit method, which allocates the majority of the emissions to electricity, and with average electricity from the grid, CHP leads to significantly higher emissions. Furthermore, since the benefit method allocates the majority of the emissions to electricity, the consequential emissions from the CHP utilization in Härmälänranta would be much higher. This issue is discussed further in Section 3.2.2.

With the marginal electricity assumption a very important decision is which fuel and technology is selected to describe the marginal production. In Finland it has traditionally been coal condensing, which leads to by far the highest emissions in our assessment and gives a clear preference to CHP. However, the global market prices of fuels define the fuel utilization in the long run. Furthermore, electricity imports and the wide interest in eliminating coal as a fuel completely can significantly reduce the role of condensing coal plants as a marginal technology. Thus, the marginal options of oil and natural gas can also depict the impact of an increase in electricity demand in the case where Finnish marginal production only partially fills the demand gap.

As shown in Figure 1a,b, for oil as the marginal fuel the range in our assessment is 1020…1530 t CO_2e/a, which is already well above the CHP options. For natural gas the range is 510…1020 t CO_2e/a. This is the most interesting of the marginal options, since with the lower GHG intensity boundary HP becomes preferable to CHP in our case, but with the higher GHG boundaries the preference order is the opposite. Thus, it seems that when moving towards high efficiency gas condensation as the marginal technology, HP option becomes competitive even when HPs are assumed to push marginal production, but the exact preference order in a certain case requires detailed information about the local production conditions.

3.2.2. CHP Allocation Methods

The second problem arises from the CHP allocation methods and the electricity assumption in the CHP options. CHP can be made to seem as good an option with HP even with the average electricity assumption, if a large enough share of the GHGs from CHP is allocated to electricity. Such a method is, for example, the all-for-electricity method (see Section 2.4.). With the all-for-electricity method CHP heat with average grid electricity would lead to a range from 260 t CO_2e/a to 640 t CO_2e/a for Härmälänranta, thus highlighting the possibility to color the outcome of the analysis.

Nevertheless, the heat demand also drives the CHP electricity output. The all-for-electricity method with average grid electricity thus gives a very biased image of the actual emissions caused by the new settlement. Assigning the electricity-related emissions for the settlement based on CHP electricity thus gives very different results. The range would run from 490 t CO_2e/a to 730 t CO_2e/a depending on the fuel intensities adopted, which is virtually equal to the other CHP options with CHP electricity.

With regard to the main methods utilized in this study, the benefit method and the energy method, the differences are less extreme than with the all-for-electricity method, as Figure 1a,b show. However, comparisons of CHP with average electricity and HP with marginal electricity are not well justified overall. If HPs are assumed to drive marginal production, CHP clients should be allocated the emissions from CHP electricity as well when comparing the consequential impacts of HP and CHP as the energy solutions of a new settlement. With different fuel-mixes this issue can potentially be of much higher importance.

3.2.3. GHG Intensities of Different Fuels/Production Modes

The third issue is that the variation in the results is huge just in terms of the selected GHG intensities (including the conversion efficiency) for different fuels and production types (between Figure 1a,b), which should be only background information in the planning context. Differences of this magnitude significantly affect the importance of the energy system choice in comparison with other means to affect the emissions caused by a certain settlement and thus make robust decisions very problematic.

In addition, the ranges presented by Cherubini *et al.* (2009) [23], and utilized in this study, are by no means absolute highs/lows. Especially regarding biomass the situation is very difficult since the temporal perspective plays a major role (e.g., [42,43]). Biomass is often taken as a very low carbon option, and in Tampere as well as in Finland in general strong expectations are placed on the potential of biomass to decrease the emissions from CHP and separate heat production in the future. With the GHG intensity range of Cherubini *et al.* (2009) [23] for biomass, 54…108 g CO_2e/kWh, the 38% biomass scenario for the City of Tampere (see Section 2.2.) would reduce the GHGs caused by Härmälänranta by approximately 10% to 20% compared to the current situation. However, biomass, especially in the form of northern forests, is actually low GHG fuel only in the very long run, when the forest stocks are recovered (e.g., [42–44]). Thus, the GWP100 factors utilized might not be appropriate for assessing the impacts of biomass utilization. For example, Cherubini *et al.* (2012) [44] assess the GWP20 factor for northern forest utilization as biomass in energy production as falling approximately in the range of 400…600 g/kWh. The 38% biomass scenario could thus actually increase the emissions from the current (natural gas comparison) in the short term and only after decades improve the balance.

The timing issue has not yet been given the attention it deserves, but similar examples have been presented regarding biofuel production [45] and construction and buildings [46]. Especially since the GHG mitigation targets have been set to the relatively near future, this perspective should be given more consideration. The issue is highly complex, however. For example, if the timber were to be used for something else and only the residues used as fuel, the assessment setting would change substantially. In addition, higher demand for residues could lead to increased utilization of wood products as a whole and thus potentially increase the total volume of the natural carbon stock. Only understanding the complex overall consequential impacts would allow determining the sustainability of alternative courses of action.

3.3. Additional Perspectives

3.3.1. Relationship between CHP and Marginal Electricity Production

An often utilized argument favoring CHP is that connecting a new settlement to CHP in theory replaces the need for marginal production, assuming that the other options are direct electricity or HPs, and that they drive marginal production. Regarding a specific urban planning situation, however, evaluating this potential substitution effect is very complex. Only a fraction, if any, of the energy demand of a new settlement is actually new demand, the rest being just relocated demand. Demand at some local energy system level may be eliminated and new demand generated at the new site with potential consequential impacts, but these are virtually impossible to estimate at the planning stage. In any case the potential substitution effect is of limited scale.

In addition, if electricity from a CHP plant is seen to substitute hypothetical marginal electricity, the GHGs caused by electricity consumption at the settlement in question need to be calculated based on CHP electricity, since that is the consequential GHG load and the alternative to marginal production. The gain would thus be the difference between the emissions from the hypothetical marginal production and those from CHP. Furthermore, marginal production is not present only in grid electricity. In addition, CHP and other single plants, as well as whole district heating systems, can be operated with multiple fuels and so the marginal potential is present also within CHP and DH systems. In this study, we assumed natural gas as the only CHP fuel, but much higher intensity fuels could as well be assumed as marginal fuels for a specific plant. Thus, when true consequential impacts are analyzed, the actual fuel should be taken into account as well.

Finally, extending the assessment boundary to include imports leads to a situation where the so-called marginal demand can be met with imported electricity as well as with local or national production, which in the Finnish case is often very low-intensity Nordic hydropower. The future smart grids will also reduce the need for today's marginal production. Together with increasing renewables-based production capacity in Finland, the fossil fuels utilization is likely to decrease and less and less of such marginal production as described in this study will be needed. CHP electricity might thus become the production option with the highest GHG intensity.

3.3.2. The Impact of COP

Regarding HP technologies, we utilized a COP of 3.0 throughout the assessments. However, even currently the COP can be as high as over four (e.g., [34,40]) and in the future will presumably rise even higher. We ran the same analysis with COP 4.0 as well, but the resulting GHG reduction of 10% did not significantly affect the decision guidelines in the case of Härmälänranta. The HP with marginal coal or oil options remained as the worst options and HP with marginal gas option with the lower emissions intensities boundary, but with the upper boundary CHP remains as the preferable option even with a COP of as high as 5.0. However, in another situation with the local CHP plant operating for example with coal and peat (a viable option in Finland), this increase in COP would quickly increase the competitiveness of HP. The lower boundary of 2.6 (see Section 2.3.) would not significantly affect the results either.

4. Conclusions

This study was set to analyze how energy systems should be viewed in environmentally aware urban planning and related decision making. The choice of energy system is often the most important factor in the GHG emissions of a residential area and should thus have a very central role in the environmental considerations of urban planning. CHP has a strong push globally due to its potential to reduce the GHGs compared to separate heat and electricity production (e.g., [9,10]). However, the uncertainties in assessing the emissions from CHP and alternative options related to any specific planning situation make it very difficult to give any robust guidelines for planning. Consequently, the assessments are inevitably based on strong general assumptions instead of including the local conditions, leading potentially to biased results and unwanted GHG development in the long run. In addition to the difficulties in rating the order of preference to different energy production modes, even the order of magnitude for the emissions caused by a certain settlement is difficult to assess robustly due to the uncertainties related to the GHG intensities of different production modes, fuels and grid averages (discussed in detail e.g., in [23,25,47]).

In the study we analyzed the new residential development of Härmälänranta in Tampere, Finland, which had earlier been studied by Ristimäki *et al.* (2013) [35], who concluded that HPs should be preferred over CHP as the energy system from the perspective of GHGs. On the other hand, Rinne and Syri (2013) [34] have recently suggested just the opposite order of preference in Finnish conditions. Our results show clearly how strongly assumption-dependent any preference order actually is. We presented several very problematic issues which hinder robust decisions in any such assessment with regard to the

GHG outcome. According to our results, either option can be the preferable one in a certain operating environment, and it is actually often a very complex task to determine the preference order.

In general we suggest in this paper an assessment method in which the CHP electricity is first allocated to those demanding the heat and only the possibly remaining share is fed to the grid. This has not been the dominant method, but the justifications are clear in the context of our study: CHP electricity output follows heat production, the same sources of demand thus holding certain responsibility for electricity production as well, according to the consumer responsibility principle (e.g., [48]). Furthermore, this allocation allows a more balanced comparison between CHP and HP, since the different allocation methods have less impact on the overall emissions, as depicted in Figure 1. CHP heat clients cannot be assumed to drive marginal electricity production with their demand unless it exceeds the CHP electricity output (at a certain point of time). However, it is not fully justified to assess the electricity demand of CHP clients with a grid average, especially if HPs are assumed to drive marginal production.

The context of the study was Finland, specifically an area of Tampere, but the issue observed and the results achieved have wider relevance. Wherever heat is produced locally and electricity is provided by at least a regional grid, similar complexities are likely to occur in GHG assessments. For example, in other Nordic countries the issue is highly topical (e.g., [33,49]). Furthermore, given that CHP production is seen as a potential means to significantly help in stabilizing the global GHGs, the related complexity in GHG assessments should be better understood. For a full picture, the study should also be extended to cover the exergy perspective as well as different fuel-mixes for the CHP plant.

Acknowledgments

We thank the Academy of Finland (Grant 286747) and Tekes—the Finnish Funding Agency for Innovation (Project 984/12) for enabling the study.

Author Contributions

The first author conducted the assessments and wrote the main part of the paper. The second author participated in the research design and the assessments, collected background data and helped write parts of the paper. The third author collected data, conducted the initial calculations and helped write parts of the paper. The fourth, fifth and sixth authors were consulted about the research design and commented on the manuscript during the writing process.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. IPCC. *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Prepared by Working Group III of the Intergovernmental Panel on Climate Change*; Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., *et al.* Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2011; p. 1075.

2. IEA (The International Energy Agency). *World Energy Outlook 2008*; OECD/IEA: Paris, France, 2008; p. 569.
3. Hoornweg, D.; Sugar, L.; Trejos Gomez, C. Cities and greenhouse gas emissions: Moving forward. *Environ. Urban.* **2011**, *23*, 207–227.
4. United Nations. *City Planning Will Determine Pace of Global Warming*; UN Sixty-Second General Assembly, Second Committee; United Nations: New York, NY, USA, 2007.
5. Kenworthy, J.R. The eco-city: Ten key transport and planning dimensions for sustainable city development. *Environ. Urban.* **2006**, *18*, 67–85.
6. Glaeser, E.; Kahn, M. The greenness of cities: Carbon dioxide emissions and urban development. *J. Urban Econ.* **2010**, *67*, 404–418.
7. Seto, K.C.S.; Dhakal, A.; Bigio, H.; Blanco, G.C.; Delgado, D.; Dewar, L.; Huang, A.; Inaba, A.; Kansal, S.; Lwasa, J.E.; *et al*. Human Settlements, Infrastructure and Spatial Planning. In *Climate Change 2014: Mitigation of Climate Change*; Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., *et al.* Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014.
8. Säynäjoki, E.; Heinonen, J.; Junnila, S. The Power of Urban Planning on Environmental Sustainability: A Focus Group Study in Finland. *Sustainability* **2014**, *6*, 6622–6643.
9. IEA (The International Energy Agency). *Combined Heat and Power: Evaluating the Benefits of Greater Global Investment*; OECD/IEA: Paris, France, 2008; p. 39.
10. IEA (The International Energy Agency). Global CHP/DHC Data—Current Baseline [referred: 26.2.2015]. Available online: http://www.iea.org/chp/data/globalchpdhcdata-currentbaseline/ (accessed on 26 August 2015).
11. Berta, G.; Prato, A.; Garbarino, L. Design criteria for distributed cogeneration plants. *Energy* **2006**, *31*, 1403–1416.
12. Rajala, P.; Hirvonen, H.; Perttula, S.; Lähde, E.; Pulkka, P.; Jarmala, L.; Laukkanen, J.; Patronen, J.; Jokinen M.; Rintala, T.; *et al. Energiatehokkuus Kaavoituksessa*; Sitran selvityksiä 41; Sitra: Helsinki, Finland, 2010.
13. Lund, H.; Andersen A.N. Optimal designs of small CHP plants in a market with fluctuating electricity prices. *Energy Convers. Manag.* **2005**, *46*, 893–904.
14. IEA (The International Energy Agency). *Energy Policies of IEA Countries*; Germany, 2013 Review; OECD/IEA: Paris, France, 2013; p. 212.
15. Säynäjoki, E.; Heinonen, J.; Junnila, S. Role of Urban Planning in Encouraging More Sustainable Lifestyles. *J. Urban Plan. Dev.* **2014**, *141*, 04014011.
16. Heinonen, J.; Junnila, S. Residential energy consumption patterns and the overall housing energy requirements of urban and rural households in Finland. *Energy Build.* **2014**, *76*, 295–303.
17. Neuman, M. The Compact City Fallacy. *J. Plan. Educ. Res.* **2005**, *25*, 11–26.
18. Holden, E.; Norland, I. Three Challenges for the Compact City as a Sustainable Urban Form: Household Consumption of Energy and Transport in Eight Residential Areas in the Greater Oslo Region. *Urban Stud.* **2005**, *42*, 2145–2166.
19. Björklund, A. Survey of Approaches to Improve Reliability in LCA. *Int. J. Life Cycle Assess.* **2002**, *7*, 64–72.

20. McCarthy, R.; Yang, C. Determining marginal electricity for near-term plug-in and fuel cell vehicle demands in California: Impacts on vehicle greenhouse gas emissions. *J. Power Sources* **2010**, *195*, 2099–2109.
21. Mathiesen, B.; Münster, M.; Fruergaard, T. Uncertainties related to the identification of the marginal energy technology in consequential life cycle assessments. *J. Clean. Product.* **2009**, *17*, 1331–1338.
22. Lund, H.; Mathiesen, B.; Christensen, P.; Schmidt, J. Energy system analysis of marginal electricity supply in consequential LCA. *Int. J. Life Cycle Assess.* **2010**, *15*, 260–271.
23. Cherubini, F.; Birda, N.; Cowie, A.; Jungmeier, G.; Schlamadinger, B.; Woess-Gallasch, S. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resourc. Conserv. Recycl.* **2009**, *53*, 434–447.
24. Curran, M.; Mann, M.; Norris, G. The international workshop on electricity data for life cycle inventories. *J. Clean. Product.* **2005**, *13*, 853–862.
25. Soimakallio, S.; Kiviluoma, J.; Saikku, L. The complexity and challenges of determining GHG (greenhouse gas) emissions from grid electricity consumption and conservation in LCA (life cycle assessment)—A methodological review. *Energy* **2011**, *36*, 6705–6713.
26. Plevin, R.; Delucchi, M.; Creutzig, F. Using Attributional Life Cycle Assessment to Estimate Climate-Change Mitigation Benefits Misleads Policy Makers. *J. Ind. Ecol.* **2013**, *18*, 73–83.
27. Lund, H. Renewable energy strategies for sustainable development. *Energy* **2007**, *32*, 912–919.
28. IEA (The International Energy Agency). *Nordic Energy Technology Perspectives—Pathways to a Carbon Neutral Energy Future*; OECD/IEA: Paris, France, 2012; p. 211.
29. Ipakchi, A.; Albuyel, F. Grid of the Future. Are We Ready to Transition to a Smart Grid? *IEEE Power Energy Mag.* **2009**, 52–64, doi:10.1109/MPE.2008.931384.
30. Lew, D.; Brinkman, G.; Ibanez, E.; Florita, A.; Heaney, M.; Hodge, B.-M.; Hummon, M.; Stark, G.; King, J.; Lefton, S.A.; *et al. The Western Wind and Solar Integration Study Phase 2: National Renewable Energy Laboratory*; Technical Report NREL/TP-5500–55588; NREL: Denver, CO, USA, 2013; p. 244.
31. Katzenstein, W.; Apt, J. Air emissions due to wind and solar power. *Environ. Sci. Technol.* **2009**, *43*, 253–258.
32. Frischknecht, R. Allocation in Life Cycle Inventory Analysis for Joint Production. *Int. J. Life Cycle Assess.* **2000**, *5*, 85–95.
33. Soimakallio, S.; Saikku, L. CO_2 emissions attributed to annual average electricity consumption in OECD (Organization for Economic Co-operation and Development). *Energy* **2012**, *38*, 13–20.
34. Rinne, S.; Syri, S. Heat pump *versus* combined heat and power production as CO_2 measures in Finland. *Energy* **2013**, *57*, 308–318.
35. Ristimäki, M.; Säynäjoki, A.; Heinonen, J.; Junnila, S. Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design. *Energy* **2013**, *63*, 168–179.
36. Statistics Finland Official Statistics of Finland (OSF): Households' Consumption [e-publication]. ISSN=2323-3028. Helsinki: Statistics Finland. Available online: http://stat.fi/til/ktutk/tau_en.html (accessed on 12 February 2015).

37. Statistics Finland Official Statistics of Finland (OSF): Energiavuosi 2012 (Energy year 2012), [e-publication]. ISSN=1796–0479. Helsinki: Statistics Finland. Available online: http://pxweb2.stat.fi/sahkoiset_julkaisut/energia2013/html/suom0016.htm (accessed on 12 February 2015).
38. Kara, M.; Syri, S.; Lehtilä, A.; Helynen, S.; Kekkonen, V.; Ruska, M.; Forsström, J. The impacts of EU CO_2 emissions trading on electricity markets and electricity consumers in Finland. *Energy Econ.* **2008**, *30*, 193–211.
39. Vartiainen, E.; Luoma, P.; Hiltunen, J.; Vanhanen, J. *Hajautettu Energiantuotanto: Teknologia, Polttoaineet Markkinat ja CO_2-Päästöt*; Gaia Group Oy: Helsinki, Finland, 2002; p. 90.
40. Kuronen, M.; Junnila, S.; Majamaa, W.; Niiranen, I. Public-private-people partnership as a way to reduce carbon dioxide emissions from residential development. *Int. J. Strategic Property Manag.* **2010**, *14*, 200–216.
41. Nystedt, Å.; Sepponen, M.; Virtanen, M. *Ekotaajaman Suunnitteluperiaatteet*; VTT: Espoo, Finland, 2012.
42. Cherubini, F.; Peters, G.; Berntsen, T.; Strømman, A.; Hertwich, E. CO_2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. *GCB Bioenergy* **2011**, *3*, 413–426.
43. Helin, T.; Sokka, L.; Soimakallio, S.; Pingoud, K.; Pajula, T. Approaches for inclusion of forest carbon cycle in life cycle assessment—A review. *GCB Bioenergy* **2013**, *5*, 475–486.
44. Cherubini, F.; Bright, R.; Strømman, A. Site-specific global warming potentials of biogenic CO_2 for bioenergy: Contributions from carbon fluxes and albedo dynamics. *Environ. Res. Lett.* **2012**, *7*, 045902.
45. Schwietzke, S.; Griffin, W.; Matthews, H. Relevance of emissions timing in biofuel greenhouse gases and climate impacts. *Environ. Sci. Technol.* **2011**, *45*, 8197–8203.
46. Säynäjoki, A.; Heinonen, J.; Junnila, S. A scenario analysis of the life cycle greenhouse gas emissions of a new residential area. *Environ. Res. Lett.* **2012**, *7*, 034037.
47. Blum, P.; Campillo, G.; Münch, W.; Kölbel, T. CO_2 savings of ground source heat pump systems—A regional analysis. *Renew. Energy* **2010**, *35*, 122–127.
48. Lenzen, M.; Murray, J.; Sack, F.; Wiedmann, T. Shared producer and consumer responsibility—Theory and practice. *Ecol. Econ.* **2007**, *61*, 27–42.
49. Slagstad, H.; Brattebø, H. Use of LCA to evaluate solutions for water and waste infrastructure in the early planning phase of carbon-neutral urban settlements. *Smart Sustain. Built Environ.* **2013**, *2*, 28–42.

Journal of Sustainable Development of Energy, Water and Environment Systems

http://www.sdewes.org/jsdewes

Year 2020, Volume 8, Issue 2, pp 360-372

Uncertain Greenhouse Gas Implication in Waste Heat Utilization – A Case Study with a Data Center

Jani Laine*[*1], Kaisa Kontu[2], Jukka Heinonen[3], Seppo Junnila[4]

[1]Department of Built Environment, School of Engineering, Aalto University, P.O. Box 11000
(Otakaari 24), FI-00076 Aalto, Finland
e-mail: jani.laine@aalto.fi
[2]Department of Built Environment, School of Engineering, Aalto University, P.O. Box 11000
(Otakaari 24), FI-00076 Aalto, Finland
e-mail: kaisa.kontu@aalto.fi
[3]Faculty of Civil and Environmental Engineering, University of Iceland, Sæmundargata 2,
101 Reykjavík, Iceland
e-mail: heinonen@hi.is
[4]Department of Built Environment, School of Engineering, Aalto University, P.O. Box 11000
(Otakaari 24), FI-00076 Aalto, Finland
e-mail: seppo.junnila@aalto.fi

Cite as: Laine, J., Kontu, K., Heinonen, J., Junnila, S., Uncertain Greenhouse Gas Implication in Waste Heat Utilization – A Case Study with a Data Center, J. sustain. dev. energy water environ. syst., 8(2), pp 360-372, 2020,
DOI: https://doi.org/10.13044/j.sdewes.d7.0301

ABSTRACT

Waste heat utilization is shown to have the potential to decrease greenhouse gas emissions globally. The purpose of this case study is to illustrate how the utilization of waste heat to decrease municipal boundary greenhouse gas emissions may increase such emissions within wider boundaries. The case study assesses the utilization of waste heat generated by a data center. In this paper, we analyze the implications within Scopes 1-3 of the Greenhouse Gas Protocol together with attributional and consequential life cycle assessment principals. Only Scope 1 showed negative greenhouse gas emission implications. In order to achieve negative Scope 2 emissions, approximately half of the waste heat would need to be utilized, which is the purpose of further site development. In order for negative Scope 3 emission implications, electricity production changes are needed or local municipal replaceable greenhouse gas emissions would need to be much higher.

KEYWORDS

Climate change mitigation, Greenhouse gas inventory, Life cycle assessment, Energy systems, Greenhouse gas protocol.

INTRODUCTION

Energy accounts for over 70% of total Greenhouse Gas (GHG) emissions [1], and the share of energy-related GHG emissions caused by cities have been estimated to account for over 70% [2]. This highlights the mitigating role of cities in energy-related GHG emissions and climate change in general. In favor of this, it has been shown that cities are efficient in promoting national energy policies (e.g. [3, 4]).

---

[*] Corresponding author

Utilization of waste heat has a powerful potential to reduce GHG emissions globally [5]. The original idea of the District Heating (DH) system is that heat can be recycled from sources where it would otherwise be wasted [6]. For instance, in the Nordic countries, where DH has a long tradition and the total supply of DH is 130 TWh/year [7, 8], heat for the DH network is produced in centralized heating plants, such as Combined Heat and Power (CHP) plants, which in most cases is a versatile fuel mix.

Despite high figures for the amount of CHP in DH systems, the amount of industrial waste heat used as a heat source in DH systems is still low, even though it is regarded as a vital means of increasing energy efficiency. In the new heat roadmap for Europe, Connolly *et al*. [9] mapped the yearly potential of industrial excess heat in DH networks in the EU27 countries for 2,710 PJ, which is almost twice as much as the total DH in 2010. The amount of industrial excess heat used in DH networks accounted for only 0.9% of the mapped potential in the year 2010 [9]. In Sweden, the amount of industrial waste heat used in DH systems was the highest out of all these countries in 2011 – it accounted for 7% (3,852 GWh) of the total fuel input [10]. The potential of industrial waste heat utilization is also studied in China [11], Spain [12], and Croatia [13]. Although the potential of industrial waste heat is shown to be significant, the actual GHG impacts are unclear when heat pumps are needed to increase the temperature of utilized waste heat to be suitable for DH network. Although waste heat as itself can be GHG emission free, energy used to increase and distribute the heat may not be. Thus, assessment of the GHG emission implications is needed in order to understand actual GHG emissions. However, assessment of such implications is relatively complex.

For GHG assessment, three different scopes have been suggested by the GHG Protocol Corporate Standard [14]. Scope 1 emissions are direct GHG emissions from sources within the city boundary. Scope 2 expands the definition by including GHG emissions occurring as a consequence of the grid supplied electricity, heat, steam, and/or cooling within the city boundaries. Scope 3 further expands the definition by including all the other GHG emissions outside the city boundaries caused by activities within the city boundaries. For stationary energy-related assessments, the difference between Scope 2 and Scope 3 is that Scope 3 also includes indirect GHG emissions from the use of energy. Scopes 1-3 together form the carbon footprint of the studied object, e.g. an individual, a city, or a nation – following the definition of Wiedmann and Minx [15].

In addition to indirect emissions, consequential implications also occurred from the actions needed to be recognized in order to have a comprehensive understanding. Life Cycle Assessment (LCA) is a method capable of accounting for the global impact of activities taking place in a certain geographic region. From the perspective of how global implications are accounted for, there are two approaches for LCA – Attributional and Consequential LCA (ALCA & CLCA). The first only accounts for the emissions through the production and delivery chains, whereas the latter tries to capture the related change in the system in general, following a change in one component. These two approaches can thus lead to completely different perceptions of the matter and ALCA, thus misleading policy makers [16]. Especially in the electricity grid, the CLCA approach increases the GHG implications [17] and has also emphasized effects on cities' carbon footprints [18].

For a city-level assessment of energy-related impacts, although often needed to understand the actual implications, the CLCA approach complicates the assessment of impacts and the decision-making regarding energy choices [19]. Energy systems, the utilization of energy sources, and relevant matters need to be assessed based on consequential impacts as well when the assessment is based on the CLCA approach. Within energy system studies, consequential system impacts are well-studied and often referred to as marginal system impacts [20]. Marginal energy impacts are changes made to an energy production system and production portfolio. Marginal production technology is usually the most expensive and most harmful to the environment. This potentially improves the efficiency made through limiting energy demand, but it increases the relevance of consequential implications occurred from the increase in energy demand.

Despite the broad existing research in the areas of assessment methods and waste heat utilization, the actual GHG emission implications from waste heat utilization and from the ALCA and CLCA perspectives within different scopes is a relatively untouched area. Such implications are important to understand when reaching negative GHG emission implications within municipal and national boundaries. Understanding of consequential implications when waste heat replaces alternative energy source but utilize other is beneficial when identifying the conditions in which negative GHG emission implications are evident. Additionally, understanding of consequential implications is important when deciding where to place waste heat sources.

This case study assesses a case where a data center is located in a city and its waste heat is utilized within the municipal DH system, replacing natural gas as a heat source. The case has been previously assessed from the technical and economic perspectives, and it was proposed that CLCA would be an appropriate approach for GHG implication assessment [21]. The case study assesses GHG emission implications within GHG Protocol's Scopes 1-3, as proposed in the previous case study. The CLCA perspective is included and considered within Scope 3 assessments. The purpose is to illustrate how utilization of waste heat to decrease municipal-bounded GHG emissions can lead to an increase in GHG emissions within wider boundaries.

METHODS AND MATERIAL

Mäntsälä is a small city with 20,853 inhabitants (2016) located in southern Finland. The city of Mäntsälä owns the company Nivos Energia Oy, which itself owns a DH network. DH production is covered with Heat-Only Boilers (HOB) located along the city, where natural gas plays a major role, as shown in Figure 1 and Table 1. A major new electricity consumption unit was added in 2016 when a data center was built. The site and detailed spatial location were chosen so that it was technically feasible to utilize the waste heat in a municipal energy system and DH network.

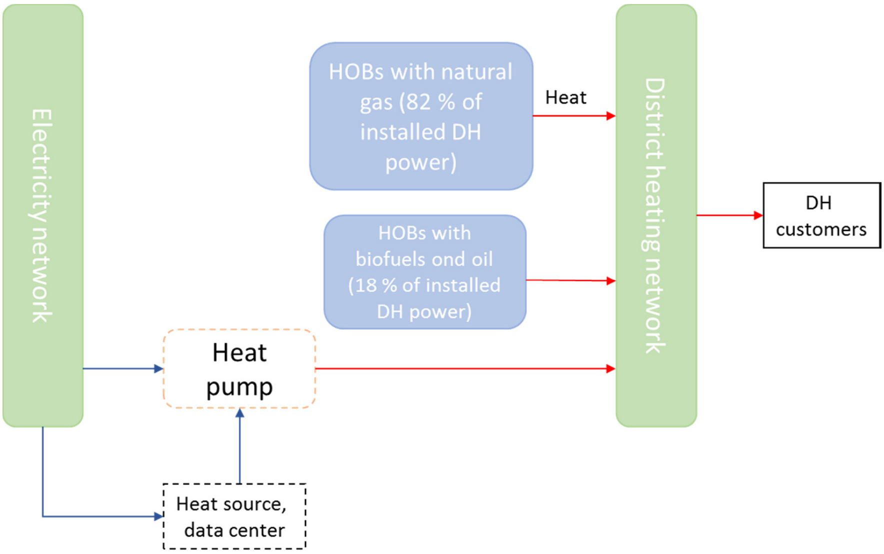


Figure 1. DH network production in Mäntsälä

Table 1. Information of DH network in Mäntsälä 2016 [22]

DH production specifications	
Number of HOBs	11
Length of the heating network [km]	37.2
Number of consumer points	210
Customer contract power total	38.1
Net production [GWh]	54.4
Heat supply [GWh]	54.4
Heat consumption [GWh]	44.0
Heat delivery and losses [GWh]	10.4
Boiler conversion losses [%]	10
Fuels	
Light oil [GWh]	2.8
Natural gas [GWh]	30.5
Bio fuels [GWh]	8.7
Heat pump supply [GWh]	16.1
Light oil [CO_2eq/kWh]	261.7
Natural gas [CO_2eq/kWh]	198.1
Bio fuels [CO_2eq/kWh]	0

The assessment methods employed in the study are based on ALCA and CLCA as well as direct GHG emission assessment. Assessment boundaries are GHG Protocol's Scopes 1-3 where ALCA and CLCA is performed within their scope. For Scopes 1 and 2, only direct emissions are considered. The Scope 1 boundary definition used is a city's own direct production emissions. For Scope 2, Scope 1 emissions are added by direct emissions from energy use that is produced outside the city boundaries. In this case, such emissions occurred from the electricity supplied from the grid. For Scope 3, the boundary is the national border and the Finnish grid with indirect emissions from energy production. For a consequential implication in CLCA, marginal electricity production is assumed to be national condensing power production with its average emissions calculated as presented in Table 2. The CLCA approach is limited to cover only instant marginal energy emission implications. Thus, wider consequential system implications are excluded.

Table 2. Calculation definitions and principals

	Scope	LCA	Out-of-jurisdiction implications	GHG emission range's minimum (L) or maximum (H) values [direct only (D)]	Calculation of energy-based emission implications
Scope 1 emission implications	1	A	+	D	$C_{\mathrm{imp}} = -E_{\mathrm{h}} \times \mathrm{GHG}_{\mathrm{ng}}$
Scope 2 emission implications	2	A	+	D	$C_{\mathrm{imp}} = -E_{\mathrm{h}} \times \mathrm{GHG}_{\mathrm{ng}} + E_{\mathrm{p}} \times \mathrm{GHG}_{\mathrm{el}} + E_{\mathrm{d}} \times \mathrm{GHG}_{\mathrm{el}}$
Scope 2 emission implications excluding out-of-jurisdiction implications	2	A	-	D	$C_{\mathrm{imp}} = -E_{\mathrm{h}} \times \mathrm{GHG}_{\mathrm{ng}} + E_{\mathrm{p}} \times \mathrm{GHG}_{\mathrm{el}}$
Scope 3 emission implications (minimum values for emissions)	3	A	+	L	$C_{\mathrm{imp}} = -E_{\mathrm{h}} \times \mathrm{GHG}_{\mathrm{ngl}} + E_{\mathrm{p}} \times \mathrm{GHG}_{\mathrm{ell}} + E_{\mathrm{d}} \times \mathrm{GHG}_{\mathrm{ell}}$
Scope 3 emission implications excluding out-of-jurisdiction implications (minimum values for emissions)	3	A	-	L	$C_{\mathrm{imp}} = -E_{\mathrm{h}} \times \mathrm{GHG}_{\mathrm{ngl}} + E_{\mathrm{p}} \times \mathrm{GHG}_{\mathrm{ell}}$
Scope 3 emission implications (maximum values for emissions)	3	A	+	H	$C_{\mathrm{imp}} = -E_{\mathrm{h}} \times \mathrm{GHG}_{\mathrm{ngm}} + E_{\mathrm{p}} \times \mathrm{GHG}_{\mathrm{elm}} + E_{\mathrm{d}} \times \mathrm{GHG}_{\mathrm{elm}}$
Scope 3 emission implications excluding out-of-jurisdiction implications (maximum values for emissions)	3	A	-	H	$C_{\mathrm{imp}} = -E_{\mathrm{h}} \times \mathrm{GHG}_{\mathrm{ngm}} + E_{\mathrm{p}} \times \mathrm{GHG}_{\mathrm{elm}}$
Scope 3 emission implications CLCA (minimum values for emissions)	3	C	+	L	$C_{\mathrm{imp}} = -E_{\mathrm{h}} \times \mathrm{GHG}_{\mathrm{ngl}} + E_{\mathrm{p}} \times \mathrm{GHG}_{\mathrm{ellmarg}} + E_{\mathrm{d}} \times \mathrm{GHG}_{\mathrm{ellmarg}}$
Scope 3 emission implications CLCA excluding out-of-jurisdiction implications (minimum values for emissions)	3	C	-	L	$C_{\mathrm{imp}} = -E_{\mathrm{h}} \times \mathrm{GHG}_{\mathrm{ngl}} + E_{\mathrm{p}} \times \mathrm{GHG}_{\mathrm{ellmarg}}$
Scope 3 emission implications CLCA (maximum values for emissions)	3	C	+	H	$C_{\mathrm{imp}} = -E_{\mathrm{h}} \times \mathrm{GHG}_{\mathrm{ngm}} + E_{\mathrm{p}} \times \mathrm{GHG}_{\mathrm{elmmarg}} + E_{\mathrm{d}} \times \mathrm{GHG}_{\mathrm{elmmarg}}$
Scope 3 emission implications CLCA excluding out-of-jurisdiction implications (maximum values for emissions)	3	C	-	H	$C_{\mathrm{imp}} = -E_{\mathrm{h}} \times \mathrm{GHG}_{\mathrm{ngm}} + E_{\mathrm{p}} \times \mathrm{GHG}_{\mathrm{elmmarg}}$

C_{imp} = GHG implications [t CO_2]
E_{h} = Supplied heat energy from the heat pump unit [GWh]
$\mathrm{GHG}_{\mathrm{ng}}$ = CO_2eq of natural gas and boiler-based district heat [t CO_2/GWh]
E_{p} = Electricity used by the heat pump [GWh]
$\mathrm{GHG}_{\mathrm{el}}$ = Direct CO_2eq of electricity from the grid [t CO_2/GWh]
E_{d} = Electricity used by the data center [GWh]
$\mathrm{GHG}_{\mathrm{ngl}}$ = Direct + indirect CO_2eq of natural gas and boiler-based district heat (lowest emission value from the range) [t CO_2]
$\mathrm{GHG}_{\mathrm{ell}}$ = Direct + indirect CO_2eq of electricity (lowest emission value from the range) [t CO_2/GWh]
$\mathrm{GHG}_{\mathrm{ngm}}$ = Direct + indirect CO_2eq of natural gas and boiler-based district heat (highest emission value from the range) [t CO_2/GWh]
$\mathrm{GHG}_{\mathrm{elm}}$ = Direct + indirect CO_2eq of electricity (highest emission value from the range) [t CO_2/GWh]
$\mathrm{GHG}_{\mathrm{ellmarg}}$ = Direct + indirect CO_2eq of marginal electricity (lowest emission value from the range) [t CO_2/GWh]
$\mathrm{GHG}_{\mathrm{elmmarg}}$ = Direct + indirect CO_2eq of marginal electricity (maximum emission value from the range) [t CO_2/GWh]

The assessments consider the emission implications rather than the complete emissions of the city. Implications are specified to cover implications from the integration of the data center as well as the utilization of the waste heat generated. Energy consumption units are the data center and the heat pump unit, which is owned by the municipal DH company. Waste heat replaces the natural gas-based boiler, and such emission mitigation implications are considered to be emission-negative.

Assessments in Scopes 2 and 3 also consider data center energy usage as an out-of-jurisdiction actor for the municipality, presenting only in-jurisdiction GHG emission implications as defined by GHG Protocol's Policy and Action Standard [23], but including the heat pump's electricity usage, as it is owned by the municipal energy company. The purpose of this is to compare results when it is assumed that the specific energy use would exist regardless.

For the supplied heat, direct GHG emission implications are calculated from the emissions from the production of the energy excluding network losses, which are considered to be equal. For electricity production and with ALCA and CLCA, network losses are also considered.

Eleven different assessments are performed with different boundaries and assessment methods. Table 2 presents assessment calculation definitions and principals.

The research study utilizes public and site-specific data sources for the GHG implication assessments. Site-specific energy measurements are used to measure actual energy inputs and outputs, and national energy statistics are used to calculate direct emissions from the use of energy. For the indirect energy emissions, a study by Cherubini *et al.* [24] is used to specify uncertainty ranges.

Site-specific energy measurements are based on real-time energy monitoring of the data center, the heat pump unit, and the municipal DH company from 2016. Both purchased electricity and supplied heat are monitored by the data center and reported monthly. The heat pump unit operated by the municipal DH company is reported accordingly. Table 3 presents the monthly energy input and output of the data center.

Table 3. Energy input-output of the site under analysis

	Consumed electricity (heat pump) [MWh]	Supplied heat from the heat pump [MWh]	Supplied heat from the data center [MWh]	Coefficient of Performance	Consumed electricity (data center) [MWh]
January 2016	331	1,042	663	3.2	3,411
February 2016	326	1,016	807	3.1	3,335
March 2016	387	1,167	593	3	3,730
April 2016	521	1,624	470	3.1	3,746
May 2016	284	851	586	3	4,019
June 2016	245	746	576	3	3,820
July 2016	248	752	476	3	4,034
August 2016	408	1,341	927	3.3	4,277
September 2016	470	1,552	1,176	3.3	4,183
October 2016	627	2,060	1,333	3.3	4,380
November 2016	621	2,063	1,420	3.3	4,363
December 2016	641	2,124	663	3.3	4,784

Statistics Finland and the Finnish energy industry are compiling monthly electricity production of CO_2 emissions based on the energy allocation method. Table 4 presents monthly electricity CO_2 emissions within Finland. These values are used to calculate monthly direct emission implications occurring from the consumption of electricity when ALCA is performed. The relatively low emissions during the summer is due to decreased consumption and thus decreased production of higher emission production plants with higher marginal cost.

Table 4. Monthly average emissions of purchased electricity from the national grid [25]

	CO_2 emissions of average electricity [t CO_2eq/GWh]
January 2016	146
February 2016	104
March 2016	104
April 2016	98
May 2016	75
June 2016	57
July 2016	38
August 2016	60
September 2016	90
October 2016	147
November 2016	155
December 2016	127

Table 5 presents monthly electricity production shares per production technology in 2016. These values are used to calculate monthly production emissions including indirect shares. Indirect emissions and emission ranges are calculated by multiplying these values with the emission ranges presented in Table 6. For thermal power production, fuel sources are presented in Table 7. For the peat emission range's lowest value, 1,150 kg CO_2eq/MWh was used, as presented by Style and Jones [26]. For the highest value, a factor between coal-based electricity production's lowest and highest values were used, giving 1,920 kg CO_2eq/MWh for the peat power production's highest value. 70 to 85 kg CO_2eq/MWh were used for emission ranges for local municipal DH, as presented in Cherubini *et al.* [24].

Table 5. Monthly 2016 electricity production shares [25]

		January	February	March	April	May	June	July	August	September	October	November	December
Hydro power	[MWh]	1,404	1,404	1,413	1,426	1,626	1,291	1,223	1,392	1,361	1,128	942	1,024
Wind power		221	235	216	198	150	201	144	292	237	250	407	516
Solar power		-	-	-	-	-	-	-	-	-	-	-	-
Nuclear power		2,064	1,928	2,061	1,840	1,503	1,692	1,987	1,702	1,606	1,950	1,985	1,961
Conv. thermal power		3,385	2,582	2,593	2,118	1,492	1,204	1,077	1,204	1,337	2,331	3,016	2,847
Co-generation		2,862	2,307	2,287	1,811	1,232	1,016	928	928	976	1,702	2,386	2,431
	District heating	1,913	1,478	1,411	1,055	533	368	238	238	422	1,048	1,632	1,651
	Industry	949	829	875	756	699	648	690	690	554	654	754	781
Condense		523	275	307	306	260	188	149	276	361	628	630	416
	Conventional	521	275	306	305	258	188	147	275	361	628	629	416
	Gasturbine, etc.	2	0	1	1	2	0	2	1	0	0	0	0
Production total		7,073	6,149	6,283	5,581	4,772	4,389	4,431	4,590	4,542	5,659	6,349	6,349

Table 6. Emission ranges for energy production including indirect emissions [24]

	Lowest values	Highest values
	[t CO_2eq/GWh]	
Biomass	54	108
Wind	4	36
Hydro	2	36
Solar	54	144
Coal	1,080	1,800
Oil	720	1,080
Nuclear	18	108
Natural gas	360	720

Table 7. Thermal power production fuel sources in 2016 [27]

	Electricity [GWh]
Condensing production	
Oil	66
Coal	2,084
Natural gas	25
Other fossil-based	508
Peat	448
Wood industry's waste liquors	338
Other wood sources	708
Other renewables	90
Other sources	51
Total	4,319
Cogeneration	
Oil	103
Coal	4,468
Natural gas	3,617
Other fossil based	405
Peat	2,284
Wood industry's waste liquors	5,031
Other wood sources	4,105
Other renewables	577
Other sources	291
Total	20,880

RESULTS

This section presents the results within the reference year of 2016. Additionally, this section presents the results when it is assumed that half of the waste heat would be utilized, as it is the purpose of the further site development.

Results within the reference year

Figure 2 presents monthly-based assessment results of the reference year within Scopes 1-3. Seven different scope and assumption setups are included: Scope 1 implications, Scope 2 implications, including and excluding an out-of-jurisdiction actor, and Scope 3 implications, including and excluding an out-of-jurisdiction actor and with the minimum and maximum range in energy emission. It is shown that Scope 1 together with Scopes 2 and 3 when out-of-jurisdiction is excluded have a similar amount of negative GHG emission implications. When Scopes 2 and 3 are assessed with in-jurisdiction implications, the results show GHG emission positive implications. Scope 2 with in-jurisdiction implications shows the lowest GHG emission implications of these, reaching negative implications in July and August. Scope 3 with a minimum range of values for energy emissions shows the second highest implications, and a similar same scope with maximum range values for energy emissions shows the highest.

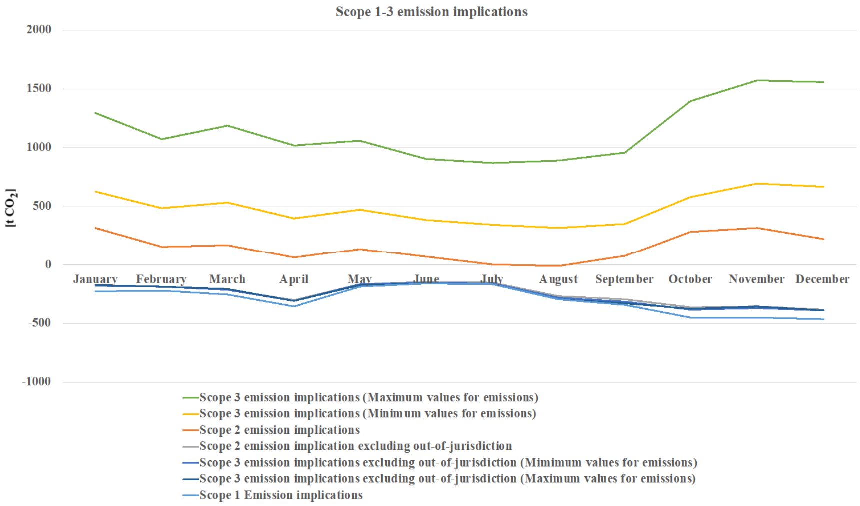


Figure 2. Scopes 1-3 emission implications in 2016 (the second Scope 2 assessment excludes data center electricity usage as an out-of-jurisdiction actor, Scope 3 assessments consider indirect emissions and emission uncertainty ranges as well, although the energy system's performance is closer to the lowest values)

Figure 3 presents Scope 3 assessment results with CLCA and the condensing power production marginal energy perspective. Four different assumption setups are assessed – Scope 3 including and excluding out-of-jurisdiction implications and with minimum and maximum range values for energy emissions. The results show that all the assumption setups show positive GHG emission implications. When excluding out-of-jurisdiction, assessments shows relatively low implications. The reason why the Scope 3 emission implications excluding out-of-jurisdiction implications show lower emission implications with maximum values is due to the relatively big decrease in locally used natural gas in relation to the increased consumption of electricity, both with higher GHG emission values. When out-of-jurisdiction is included, GHG emission implications are significant.

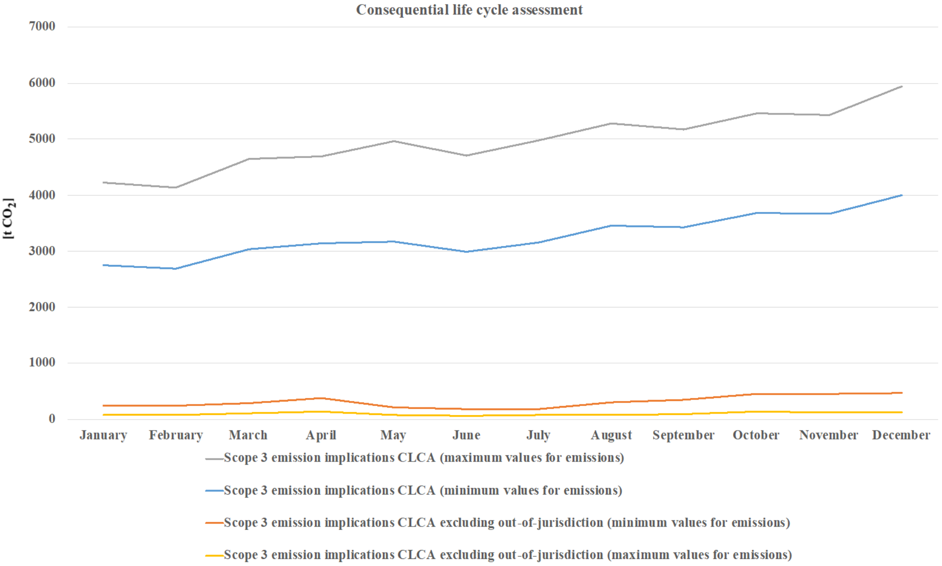


Figure 3. Consequential life-cycle assessment implications in 2016, where a condensing production fuel mix is considered to act as marginal energy production. Two assessments consider data center electricity as an out-of-jurisdiction actor

Figure 4 presents annual GHG emission implications cumulatively. It is seen that the wider the boundary within the assessment is, the higher the GHG emission implications are when out-of-jurisdiction implications are included.

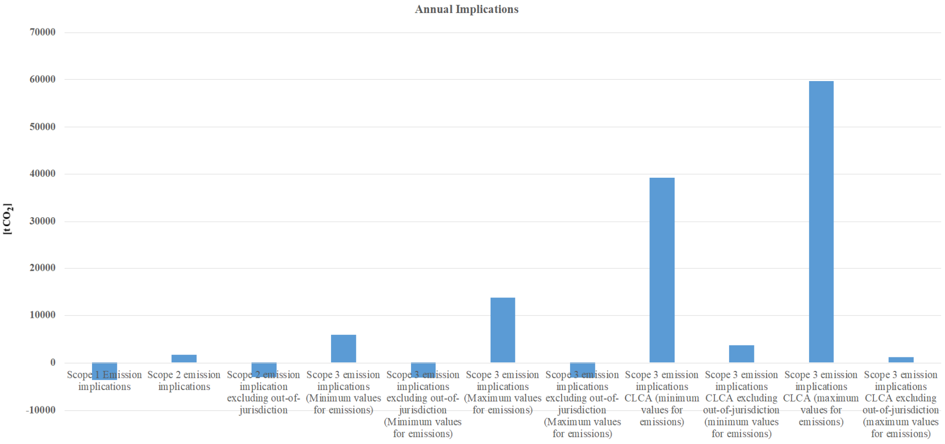


Figure 4. Annual implications within all assessments and scopes [from left to right: Scope 1 emission implications, Scope 2 emission implications, Scope 2 emission implications excluding out-of-jurisdiction, Scope 3 emission implications (minimum values for emissions), Scope 3 emission implications excluding out-of-jurisdiction (minimum values for emissions), Scope 3 emission implications (maximum values for emissions), Scope 3 emission implications excluding out-of-jurisdiction (maximum values for emissions), Scope 3 emission implications CLCA (minimum values for emissions), Scope 3 emission implications CLCA excluding out-of-jurisdiction (minimum values for emissions), Scope 3 emission implications CLCA (maximum values for emissions), and Scope 3 emission implications CLCA excluding out-of-jurisdiction (maximum values for emissions)]

Results with development assumptions

As the development plan of the site is to utilize half of the data center's electricity consumption as waste heat, it is relevant to perform such a sensitivity analysis. Figures 5-7 present the results according to previous figures and assumptions. Updated results show significant differences. Previously with ALCA-based assessments, only Scope 1 together with Scopes 2 and 3 excluding out-of-jurisdiction implications showed negative GHG emission implications. Now also Scope 2 GHG emission implications are negative, and a significant reduction is shown for every scope and assumption setup. GHG emission reduction for CLCA-based assessments are shown as well in Figure 6 and Figure 7. Now also the CLCA-based Scope 3 assessment with maximum range values for energy and out-of-jurisdiction assumptions is seen to have negative GHG emission implications.

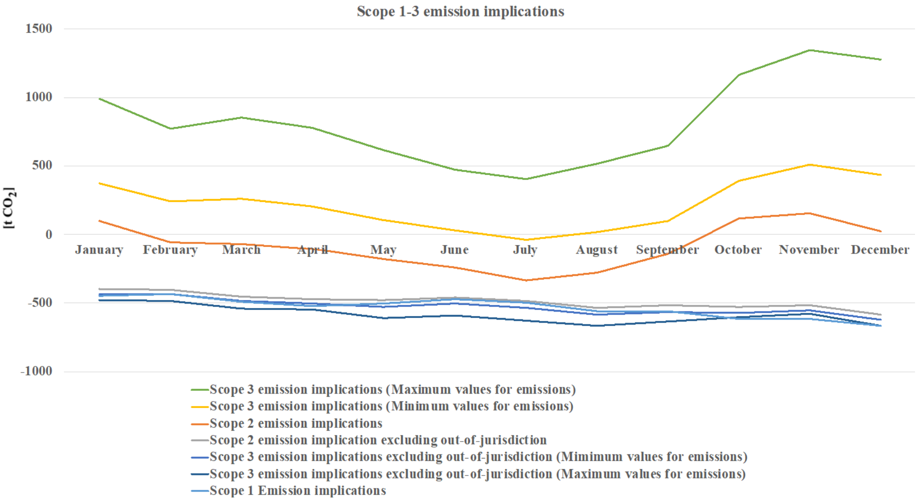


Figure 5. Scopes 1-3 assessment implications in 2016 if half of the data center electricity usage would be utilized according to the development plans

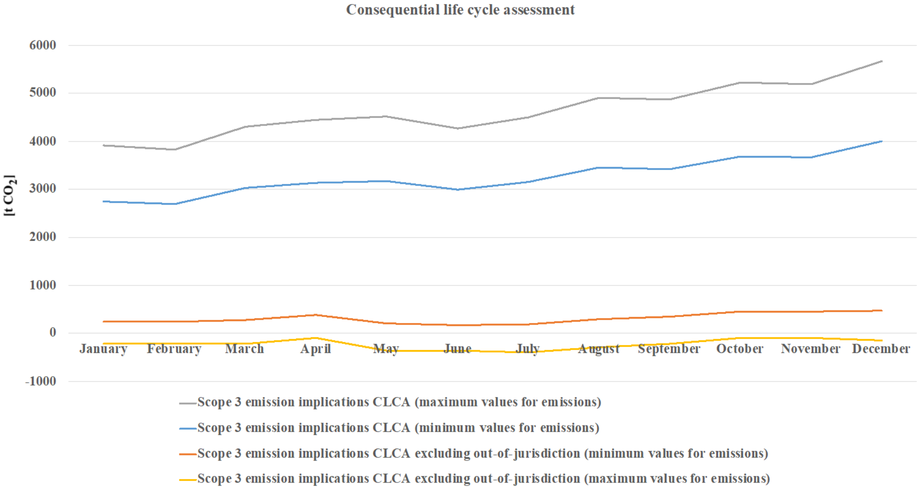


Figure 6. Consequential life-cycle assessment implications in 2016 if half of the data center electricity usage would be utilized

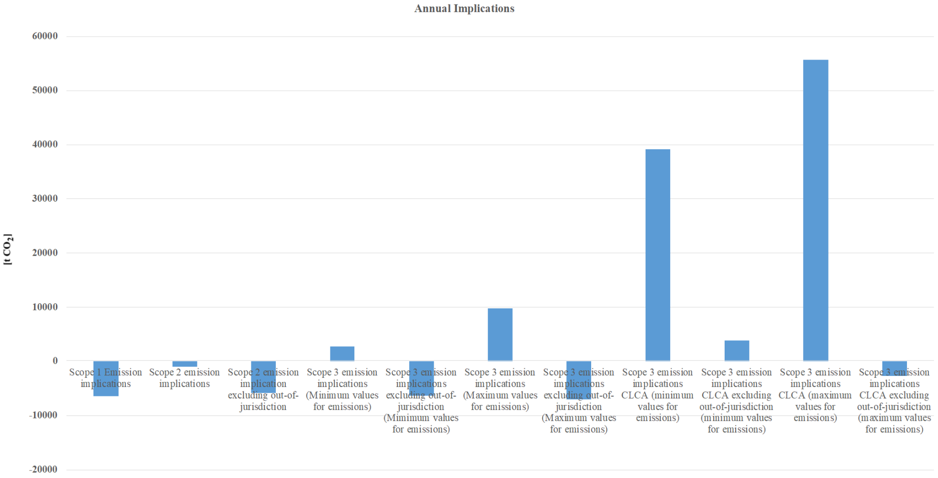


Figure 7. Annual implication within all the assessments and scopes when half of the data center electricity usage is utilized [from left to right: Scope 1 emission implications, Scope 2 emission implications, Scope 2 emission implications excluding out-of-jurisdiction, Scope 3 emission implications (minimum values for emissions), Scope 3 emission implications excluding out-of-jurisdiction (minimum values for emissions), Scope 3 emission implications (maximum values for emissions), Scope 3 emission implications excluding out-of-jurisdiction (maximum values for emissions), Scope 3 emission implications CLCA (minimum values for emissions), Scope 3 emission implications CLCA excluding out-of-jurisdiction (minimum values for emissions), Scope 3 emission implications CLCA (maximum values for emissions), and Scope 3 emission implications CLCA excluding out-of-jurisdiction (maximum values for emissions)]

DISCUSSION

The results demonstrated how utilization of waste heat to reduce municipal boundary GHG emissions can increase GHG emissions within wider boundaries. The results showed that the potential for decreasing GHG emissions as presented in studies such as [9, 13] are generalized, and actual GHG emission implications are complex to assess and may even lead to GHG emission growth.

As presented in studies such as [14-18], the results showed that the choice of assessment method and boundaries greatly affects GHG emission and emission implication results. The assessment method can even determine whether the implications are positive or negative. For municipalities, it is easy to use Scope 1 emissions and only direct emissions, as it often also accounts for the lowest emissions. However, as recommended by the GHG Protocol [24], for a more comprehensive assessment, a wider boundary needs to be used instead. This is important, as it would otherwise be relatively easy to outsource the GHG emissions. The results showed that the amount of negative emission implications shown in Scope 1 can be many times greater and positive in Scope 3.

The results also showed the importance of energy systems' marginal system implications in municipal decision making and municipal GHG emission implication contexts. The results followed previous research findings that the choice between ALCA and CLCA can lead to completely different perceptions on the matter. With the ALCA method, all the assessment results were within a relatively normal range. From the CLCA perspective, on the other hand, the results showed a significant increase in GHG emissions when out-of-jurisdiction was included.

Results also showed that when including indirect energy emission ranges to the ALCA and CLCA perspectives, the complexity even increases. This makes it hard for municipal actors to assess actual GHG emission implications.

Although the assessments were targeted to cover a significant share of assessment scopes and assumptions, numerous uncertainties still exist. Firstly, energy emission ranges were utilized covering practically all the actual production methods. One can make a site comparison between the highest ranges and between the lowest ranges, as actual alternative production methods may vary between. Secondly, a reference year was assessed instead of the lifetime of the site. As energy systems are developing, these assessment results change accordingly. Thirdly, a scenario where the data center would not be integrated was not performed. As the results were implications, this would have been important to understand especially if a lifetime assessment would have been performed.

From the national boundary point of view, the data center as an out-of-jurisdiction actor is an important matter when mitigating GHG emissions. If that actor and its electricity consumption would exist in any case somewhere within the national boundary, the question would be where to best place it and where would its waste heat generate the most GHG emission mitigation. For this purpose, the results show that the location is relatively good, even from the CLCA perspective, as the condensing power generation fuel mix would not necessarily play such a major role as a marginal production, especially when assessing within a lifetime. From the global GHG emission mitigation perspective, it is important to recognize other possible locations, which energy sources are available in those locations, and the possibility to utilize waste heat.

For extensive GHG emission impact management within different scopes, it is proposed that a municipal actor should focus on Scopes 2 and 3 GHG emission implications from the ALCA and CLCA perspectives in addition to initial Scope 1 emissions. The aim should not be to minimize Scope 1 emissions, but to identify methods to minimize Scope 1 emissions as well as Scope 2 and 3 emissions as well.

Although assessment covers different scopes with different assessment methods, there are still uncertainties that could further change the results. A major uncertainty is related to the limited CLCA used within the study. There are several possible consequences that could drastically change the outlook. First, if waste heat were not utilized, there would probably be other investments to be made to reduce local GHG emissions. Secondly, the assessment is done only for the reference year rather than the life cycle of the site. This means that development of different systems and actors are excluded, which is crucial when assessing the actual consequential implications. Thirdly, consequential implications of non-GHG emissions and larger boundary are excluded.

CONCLUSION

The case study's purpose was to show that the utilization of waste heat to decrease municipal boundary GHG emissions may increase such emissions within wider boundaries. The case study assessed Greenhouse Gas Protocol's Scopes 1-3 when waste heat generated by a data center was utilized within a municipal DH system, replacing natural gas-based heat. Although Scope 1 GHG emissions were shown to decrease, both Scope 2 and 3 GHG emissions were increased. Further development of waste heat utilization could recover half of the generated waste heat, which is enough to turn Scope 2 emissions negative. In order for negative GHG emissions within Scope 3, the location's replaceable municipal DH GHG emissions would need to be higher, such as emissions from coal with poor energy efficiency. When assessing consequential and initial electricity system impacts within Scope 3, additional electricity production changes are needed in order to realize negative GHG emission implications.

ACKNOWLEDGMENT

We thank Tekes – the Finnish Funding Agency for Innovation (Project 3000/31/15) – and Marjatta and Eino Kollin Säätiö (Grant 1102) for enabling the study. Jani Laine

conducted the research assessment, created the research design, and participated in all stages of preparing the manuscript. Kaisa Kontu conducted the energy research positioning and participated in all stages of preparing the manuscript. Jukka Heinonen and Seppo Junnila participated in the research framing and participated in all stages of preparing the manuscript.

REFERENCES

1. World Resources Institute, Climate Watch, https://www.climatewatchdata.org, [Accessed: 30-March-2019]
2. International Energy Agency (IEA), World Energy Outlook 2008, OECD/IEA, Paris, France, 2008.
3. Sperling, K., Hvelplund, F. and Mathiesen, B. V., Centralisation and Decentralisation in Strategic Municipal Energy Planning in Denmark, *Energy Policy*, Vol. 39, No. 3, pp 1338-1351, 2011, https://doi.org/10.1016/j.enpol.2010.12.006
4. Nilsson, J. S. and Mårtensson, A., Municipal Energy-Planning and Development of Local Energy-Systems, *Applied Energy*, Vol. 76, No. 1-3, pp 179-187, 2003, https://doi.org/10.1016/S0306-2619(03)00062-X
5. Firth, A., Zhang, B. and Yang, A., Quantification of Global Waste Heat and its Environmental Effects, *Applied Energy*, Vol. 235, pp 1314-1334, 2019, https://doi.org/10.1016/j.apenergy.2018.10.102
6. Werner, S., District Heating and Cooling, in: *Encyclopedia of Energy* (Cleveland, C. J., ed.), pp 841-848, Elsevier, New York, USA, 2004, https://doi.org/10.1016/B0-12-176480-X/00214-X
7. Sköldberg, H., Koljonen, T., Unger, T., Koreneff, G., Göransson, A., Alanen, R., Fritz, P., Tennbakk, B., Springfeldt, P. E., Havskjold, M., Badano, A., Langseth, B., Sandoff, A., Jakobsson, T., Schaad, G., Lehtilä, A., Niemi, J., Flyktman, M., Honkatukia, J., Pursiheimo, E., Ravn, H. and Rämä, M., Towards a Sustainable Nordic Energy System, 2010, http://www.nordicenergy.org/wp-content/uploads/2012/02/Towards-a-Sustainable-Nordic-Energy-System.pdf, [Accessed: 23-March-2018]
8. Magnusson, D., Swedish District Heating—A System in Stagnation: Current and Future Trends in the District Heating Sector, *Energy Policy*, Vol. 48, pp 449-459, 2012, https://doi.org/10.1016/j.enpol.2012.05.047
9. Connolly, D., Lund, H., Mathiesen, B. V., Werner, S., Möller, B., Persson, U., Boermans, T., Trier, D., Østergaard, P. A. and Nielsen, S., Heat Roadmap Europe: Combining District Heating with Heat Savings to Decarbonise the EU Energy System, *Energy Policy*, Vol. 65, pp 475-489, 2014, https://doi.org/10.1016/j.enpol.2013.10.035
10. Averfalk, H., Ingvarsson, P., Persson, U., Gong, M. and Werner, S., Large Heat Pumps in Swedish District Heating Systems, *Renewable and Sustainable Energy Reviews*, Vol. 79, pp 1275-1284, 2017, https://doi.org/10.1016/j.rser.2017.05.135
11. Lu, H., Price, L. and Zhang, Q., Capturing the Invisible Resource: Analysis of Waste Heat Potential in Chinese Industry, *Applied Energy*, Vol. 161, pp 497-511, 2016, https://doi.org/10.1016/j.apenergy.2015.10.060
12. Miró, L., Brueckner, S., McKenna, R. and Cabeza, L. F., Methodologies to Estimate Industrial Waste Heat Potential by Transferring Key Figures: A Case Study for Spain, *Applied Energy*, Vol. 169, pp 866-873, 2106, https://doi.org/10.1016/j.apenergy.2016.02.089
13. Bišćan, D. and Filipan, V., Potential of Waste Heat in Croatian Industrial Sector, *Thermal Science*, Vol. 16, No. 3, pp 747-758, 2012, https://doi.org/10.2298/TSCI120124123B
14. Greenhouse Gas Protocol (GHGP), 2014, http://ghgprotocol.org/sites/default/files/ghgp/standards/GHGP_GPC_0.pdf, [Accessed: 23-March-2018]
15. Wiedmann, T. and Minx, J., A Definition of 'Carbon Footprint', *Ecological Economics Research Trends*, Vol. 1, pp 1-11, 2008.

16. Plevin, R., Delucchi, M. and Creutzig, F., Using Attributional Life Cycle Assessment to Estimate Climate-Change Mitigation Benefits Misleads Policy Makers, *J. Industrial Ecology*, Vol. 18, No. 1, pp 73-83, 2013, https://doi.org/10.1111/jiec.12074
17. Soimakallio, S., Kiviluoma, J. and Saikku, L., The Complexity and Challenges of Determining GHG (Greenhouse Gas) Emissions from Grid Electricity Consumption and Conservation in LCA (Life Cycle Assessment): A Methodological Review, *Energy*, Vol. 36, No. 12, pp 6705-6713, 2011, https://doi.org/10.1016/j.energy.2011.10.028
18. Laine, J., Ottelin, J., Heinonen, J. and Junnila, S., Consequential Implications of Municipal Energy System on City Carbon Footprints, *Sustainability*, Vol. 9, No. 10, pp 1801, 2017, https://doi.org/10.3390/su9101801
19. Heinonen, J., Laine, J., Pluuman, K., Säynäjoki, E.-S., Soukka, R. and Junnila, S., Planning for a Low Carbon Future? Comparing Heat Pumps and Cogeneration as the Energy System Options for a New Residential Area, *Energies*, Vol. 8, No. 9, pp 9137-9154, 2015, https://doi.org/10.3390/en8099137
20. McCarthy, R. and Yang, C., Determining Marginal Electricity for Near-Term Plug-In and Fuel Cell Vehicle Demands in California: Impacts on Vehicle Greenhouse Gas Emissions, *J. of Power Sources*, Vol. 195, No. 7, pp 2099-2109, 2010, https://doi.org/10.1016/j.jpowsour.2009.10.024
21. Wahlroos, M., Pärssinen, M., Rinne, S., Syri, S. and Manner, J., Future Views on Waste Heat Utilization: Case of Data Centers in Northern Europe, *Renewable and Sustainable Energy Reviews*, Vol. 82, No. 2, pp 1749-1764, 2018, https://doi.org/10.1016/j.rser.2017.10.058
22. Finnish Energy Industries, Statistics 2016, Helsinki, Finland, https://energia.fi/en/, [Accessed: 20-March-2019]
23. World Resources Institute, Policy and Action Standard – An Accounting and Reporting Standard for Estimating the Greenhouse Gas Effects of Policies and Actions, http://ghgprotocol.org/sites/default/files/standards/Policy%20and%20Action%20Standard.pdf, [Accessed: 10-January-2019]
24. Cherubini, F., Birda, N., Cowie, A., Jungmeier, G., Schlamadinger, B. and Woess-Gallasch, S., Energy- and Greenhouse Gas-Based LCA of Biofuel and Bioenergy Systems: Key Issues, Ranges and Recommendations, *Resourc. Conserv. Recycl.*, Vol. 53, No. 8, pp 434-447, 2009, https://doi.org/10.1016/j.resconrec.2009.03.013
25. Finnish Energy Industries, Monthly Electricity Statistics 2016, Helsinki, Finland, https://energia.fi/en/, [Accessed: 16-March-2019]
26. Styles, D. and Jones, M. B., Energy Crops in Ireland: Quantifying the Potential Life-Cycle Greenhouse Gas Reductions of Energy-Crop Electricity, *Biomass and Bioenergy*, Vol. 31, No. 11, pp 759-772, 2007, https://doi.org/10.1016/j.biombioe.2007.05.003
27. Statistics Finland, Official Statistics of Finland (OSF), Production of Electricity and Heat, Helsinki, Finland, 2016, https://www.stat.fi/til/salatuo/2016/salatuo_2016_2017-11-02_tie_001_en.html, [Accessed: 12-January-2018]

Paper submitted: 01.04.2019
Paper revised: 06.08.2019
Paper accepted: 14.08.2019

sustainability

MDPI

Article

Pathways to Carbon-Neutral Cities Prior to a National Policy

Jani Laine [1,*], Jukka Heinonen [2] and Seppo Junnila [1]

[1] Department of Built Environment, School of Engineering, Aalto University, 00076 Aalto, Finland; seppo.junnila@aalto.fi
[2] Faculty of Civil and Environmental Engineering, University of Iceland, 107 Reykjavik, Iceland; heinonen@hi.is
* Correspondence: jani.laine@aalto.fi

Received: 24 February 2020; Accepted: 19 March 2020; Published: 20 March 2020

Abstract: Some cities have set carbon neutrality targets prior to national or state-wide neutrality targets, which makes the shift to carbon neutrality more difficult, as the surrounding system does not support this. The purpose of this paper was to evaluate different options for a progressive city to reach carbon neutrality in energy prior to the surrounding system. The study followed the C40 Cities definition of a carbon-neutral city and used the City of Vantaa in Finland as a progressive case aiming for carbon neutrality by 2030, five years before the national target for carbon neutrality. The study mapped the carbon neutrality process based on City documents and national statistics, and validated it through process-owner interviews. It was identified that most of the measures in the carbon neutrality process were actually outside the jurisdiction of the City, which outsources the responsibility for the majority of carbon neutrality actions to either private properties or national actors with broader boundaries. The only major measure in the City's direct control was the removal of carbon emissions from municipal district heat production, which potentially represent 30% of the City's reported carbon emissions and 58% of its energy-related carbon emissions. Interestingly, the City owns electricity production capacity within and beyond the city borders, but it doesn't allocate it for itself. Allocation would significantly increase the control over the City's own actions regarding carbon neutrality. Thus, it is proposed that cities aiming for carbon neutrality should promote and advance allocable carbon-free energy production, regardless of geographical location, as one of the central methods of achieving carbon neutrality.

Keywords: carbon neutral cities; greenhouse gas emissions; GHG Protocol; C40 Cities; sustainable built environment

---

1. Introduction

Seventy percent of global greenhouse gas (GHG) emissions are accounted for by cities [1], where the energy supply sector is the largest contributor of these emissions [2]. As presented by Sperling et al. [3] and Nilsson and Mårtensson [4], for instance, some cities can have highly positive attitudes towards ambitious energy policies.

Although these studies found positive willingness by cities to follow national energy policies, they also found some major weaknesses. Sperling et al. [3] identified the need for central coordination, and Nilsson and Mårtensson [4] found local energy plans often to be vague. Similarly, from an urban development perspective, several previous studies have exemplified how energy planning needs to be integrated more into urban planning and urban development processes in order to execute low carbon development effectively [5–12]. Additionally, it has been questioned whether an integrated approach to land-use and transport planning brings about the carbon emission savings often expected from the municipalities in the transport sector [13].

Despite the limitations in GHG reduction capability, numerous cities have committed to reaching carbon neutrality within a certain time, and sometimes before national carbon neutrality targets. Carbon neutrality targets have been set by New York—2050 [14], Stockholm—2040 [15], Berlin—2050 [16], London—2050 [17], and Copenhagen—2025 [18], for instance. Copenhagen's target was set prior to the national carbon neutrality target. Other cities are relying on the carbon neutrality of the energy supplied by the national grid until the target year. Due to the importance of the matter, consortiums such as Cites40 [19], Covenant of Mayors [20], and ICLEI [21] have been organized to advance the goal of carbon neutrality and general carbon reduction actions in their member cities. Cities40 is a coalition of 94 of the world's largest cities. Covenant of Mayors is an EU-established initiative implementing climate objectives in nearly 10,000 local government organizations. ICLEI is a global initiative including more than 1750 local government organizations committed to sustainable urban development, from which more than 100 have committed to carbon neutrality. Several papers have studied the efficiency of municipal energy planning and the need to integrate it more into urban planning and urban development processes. Still, research on the capability of municipalities to create actual carbon neutral cities is lacking.

In such research, the scope of choice from which the emissions that the city directly or indirectly causes are included in their assessment is of high importance. One widely recognized scope system is that of the GHG Protocol [22]. They have defined three different levels: Scope 1 refers to GHG emissions from sources located within the city boundaries; Scope 2 refers to GHG emissions occurring as a consequence of the use of grid-supplied electricity, heat, steam, and/or cooling within the city boundaries; and Scope 3 refers to all other GHG emissions that occur outside the city boundaries as a result of activities taking place within the city boundaries.

C40 Cities' definition of a carbon-neutral city [23] states four criteria for the carbon-neutral city: 1. Net-zero greenhouse gas emissions (annual emissions are completely cancelled out through carbon offsetting, or removed through carbon dioxide removal or emissions removal measures) from fuel use in buildings, transport, and industry (Scope 1), 2. Net-zero greenhouse gas emissions from the use of grid-supplied energy (Scope 2), 3. Net-zero greenhouse gas emissions from the treatment of waste generated within the city boundaries (Scope 1 and 3), and 4. Where a city accounts for additional sectoral emissions in their GHG accounting boundary, net-zero greenhouse gas emissions from all additional sectors in the GHG accounting boundary. C40 Cities also propose an alternative consumption-based approach, but the first production-based approach has been widely adopted, and is used as a definition of a carbon-neutral city in this study as well. The definition is widely used and thus justified to be used in this research. Figure 1 explains the scope definition as described by GHG Protocol [22].

In Finland, all major cities have made carbon neutrality commitments; the capital city Helsinki has committed to be carbon neutral by 2035 [24], Espoo by 2030 [25], Vantaa by 2030 [26], Tampere by 2030 [27], Turku by 2029 [28], and Oulu by 2040 [29]. The national target of carbon neutrality is set for 2035 [30], so Espoo, Vantaa, Tampere, and Turku are following the example of Copenhagen by introducing more ambitious city-level targets.

This paper's aim is to evaluate how carbon-neutral city status can be achieved when the surrounding national or state-wide system does not yet support the neutrality. The study focuses on the energy sector's GHG emissions. The research utilizes a case study of the City of Vantaa due to the availability of high-quality research material. It is conducted based on a process document review together with interviews of the key personnel who are guiding the work toward the carbon neutrality goal.

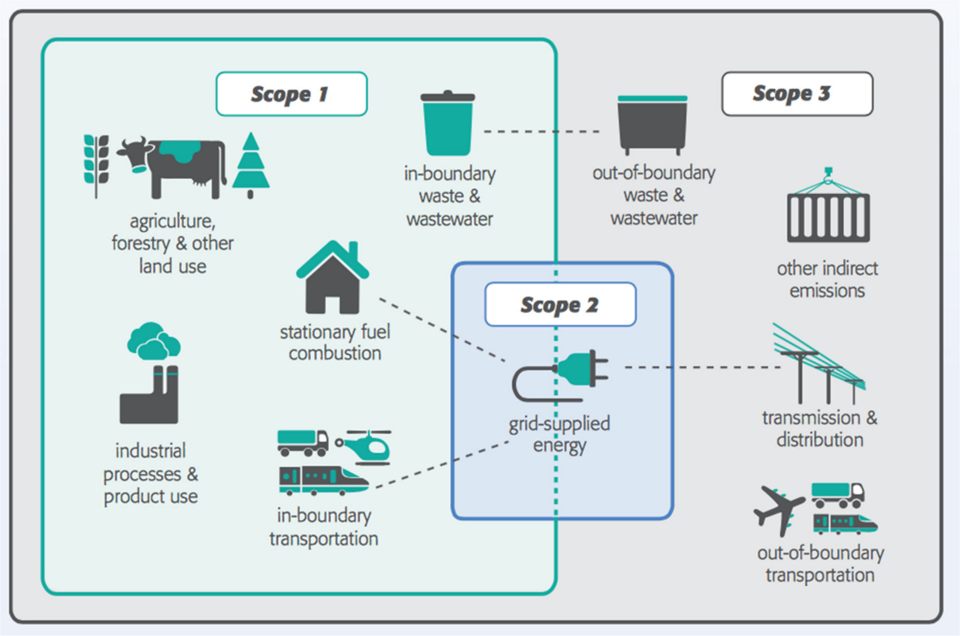


Figure 1. Scope definition by GHG Protocol [22].

It will be shown that the City under assessment outsources the majority of the actions needed to secure the status of a carbon-neutral city to the state and the private sector. In addition, it does not allocate its electricity generation from Scope 1 or 2 to itself, thus limiting its capability to reach the carbon neutrality target. When justifying such scope allocation, the potential for carbon neutrality increases dramatically and allows carbon compensation actions, for instance, to be made for other sectors as well. The paper also discusses whether cities should invest in Scope 3 energy production in order to achieve further reductions in their carbon footprint.

2. Materials and Methods

2.1. Case Setting

The case study was conducted in the third biggest city in Finland, Vantaa, which is in Southern Finland. Vantaa has 228,000 residents and 17 million gross square meters of building stock, of which 10 million is residential buildings [31]. The City's electricity consumption is 1913 GWh, and heat consumption is 1724 GWh [32]. It aims to achieve carbon neutrality by 2030 by decreasing GHG emissions by at least 80% from 1990 levels and compensate for the remainder with carbon sinks and funding carbon reduction measures elsewhere, for instance [33]. Table 1 presents a description of the City's carbon neutrality scenarios and emissions as accounted for by the City [33]. BAU is a business-as-usual scenario, describing the outcome without any additional actions, and CN describes a carbon-neutral scenario with required actions.

Table 1. Carbon-neutral city GHG (greenhouse gas) scenarios.

kt CO_2-ekv	1990	2016	2030 BAU	2030 CN	1990 Change %
District heating	271	325	188	52	−81
Oil-based heating	74	60	48	0	−100
Electricity-based heating	60	69	52	17	−72
Residential electricity	165	160	141	45	−73
Transportation	318	384	207	97	−69
Industry and machinery	95	42	16	3	−97
Waste disposal	91	35	22	0	−100
Agriculture	3	2	2	2	−53
Total	1076	1078	674	215	−80

BAU = business as usual, CN = carbon neutral [33].

As the study's focus is on the energy sector, the sub-sectors of district heating, oil-based heating, electricity-based heating, and residential electricity are within the context and are thus evaluated. Transportation, industry and machinery, waste disposal, and agriculture include emissions from sector-specific emissions sources not related to electricity or heat supply, but to land use and fuel use. The City's approach to decreasing energy sector-based GHG emissions is to eliminate oil, coal, natural gas, peat, and plastic waste from district heat production, and to decrease the consumption of electricity together while relying on national GHG reduction actions within electricity production. A more detailed action plan is described later in chapter 3. Although district heating represents a significant amount of the City's GHG emissions and is within the City's jurisdiction, oil-based heating, electricity consumption, and national-level electricity production are out-of-jurisdiction matters, and thus the plan can be considered weak as such. In addition, and as suggested by the City [33], the importance of electricity will also increase within the remaining sectors, such as transportation and industry, which are not currently within the energy sector. Tables 2 and 3 present detailed information about the energy sector's systems to which the City is connected.

Table 2. Municipal energy system details in 2016 [33–35].

Electricity Production Details		DH Production Specifications	
Electricity consumption total (GWh)	1913	Number of CHPs	3
Electricity consumption related GHG ($kgCO_2$ekv)	233,400	Number of boilers	6
CHP-based electricity production (GWh)	634	Net production (GWh)	1875.8
CHP-based electricity production related GHG (gCO_2ekv/kWh)	262	Heat delivery and losses (GWh)	152.2
Co-owned centralized electricity production (GWh)	777	Boiler conversion losses (%)	11.5
Co-owned centralized electricity production-related GHG ($kgCO_2$ekv)	0	Fuels used for heat and CHP electricity production	
Used Fuels			
Light oil (GWh)	0.4	Coal (GWh)	1199.1
Natural gas (GWh)	559.7	Municipal waste (GWh)	1057.8

Table 3. National electricity system details in 2016 [36].

Electricity Supply 2016	Total (TWh) (Used Fuels)
Hydro power	15.63
Wind power	3.07
Nuclear power	22.28 (65.01)
Conventional thermal power	25.19 (38.52)
Net imports	18.95 (18.95)

2.2. *Research Process*

The research process was twofold. The first phase was to generate the Carbon Neutrality Action Plan (CNAP) of the City's actions and process owners aiming to reach carbon-neutral city status. All of the City's direct actions are within the field of land use, buildings, and the environment [37,38]. The generation of the CNAP was performed through a review of the City's process description literature. The second phase was to validate the actions which are or were to be utilized, that were included in the CNAP. This was done by interviewing the process owners. Validation of the generated CNAP is crucial, as the literature may not represent the actual and practical processes that the City and its organizations are utilizing. Figure 2 presents the research process:

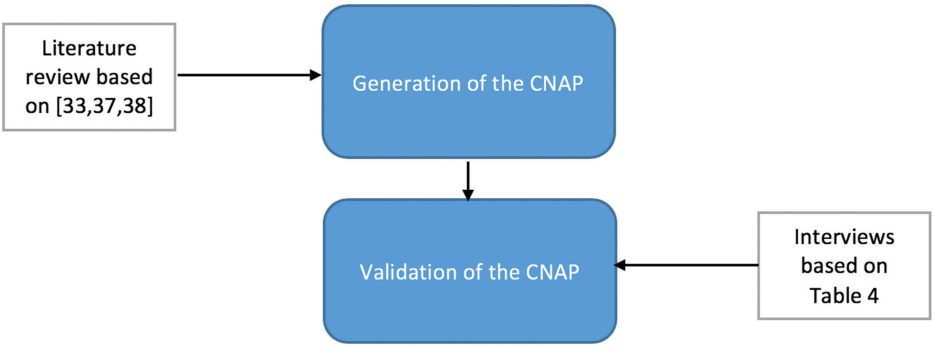


Figure 2. Research process.

2.3. *Generation of the Carbon Neutral Action Plan*

The CNAP is combined from data produced by national and municipal organizations. A document prepared by the City of Vantaa describing the required actions to achieve city-level carbon neutrality [33] has been used to describe the required technical measures. For city-level actions and process owners, a general roadmap document [37] is used for city-level process description and more detailed process description [38] for the land use, buildings, and environment sectors.

2.4. *Validation of the Carbon Neutral Action Plan*

Interviews were based on semi-structured approach and were initiated by presenting the generated CNAP, followed by discussions. The interviews focused on individuals, but were arranged in group sessions. The sessions are specified in Table 4. This may have had an impact on the responses in terms of restricting individuals to speak openly, but on the other hand, it provided support for individuals by their co-workers. In CNAP, required actions [33] are linked with processes and process owners [38]. In discussions, interviewees were asked to confirm which of these connections were correct, which weren't, and what was missing. Table 5 presents the CNAP as it was presented to the interviewees. Interviewees were presented with grand tour questions [39,40] on each numbered and required action, and were asked to explain if this was how they saw this action being managed by the City's indirect and direct processes, as described below. Planned prompts [39,41] were utilized to focus the discussion on carbon neutrality processes when explanations started to shift toward covering general city planning and development. All the interviews were recorded, transcribed, and analyzed.

Table 4. Interviewed process owners.

Interviewee	Process Ownership	Department	Interview Session
Head of Environment Center	Process owner of complete carbon-neutral city and environment	Environment Center	2, 3
Environment manager	Supporting the process owner of complete carbon-neutral city and environment	Environment Center	2, 3
Head of City Planning	Process owner of land use, buildings and environment	City Planning	3
Manager of Municipal Buildings Center	Process owner of Municipal Buildings Center	Municipal Building Center	3
Head of City Plan	Process owner of city plan	City Planning	1
Head of Master Plan	Process owner of master plan	City Planning	1
Development personnel of local municipal energy company	Process owners of municipal energy system	Municipal energy company	4

A general roadmap document [37] of the City described the process owners' response to creating a carbon-neutral city. These process owners were the City's sub-organizations. Interviewees were selected by contacting these sub-organizations and identifying the correct responsible persons. Interviewees were process owners of the municipal carbon neutrality generation process: The head of City planning (process owner of land use, buildings, and the environment), the head of the Environment Center (process owner of the complete carbon-neutral city and the environment), the environment manager (supporting the process owner of the complete carbon-neutral city and the environment), the manager of the Municipal Buildings Center (the process owner of the Municipal Buildings Center), the head of the City Plan, the head of the Master Plan and development personnel at the local municipal energy company. Table 4 presents a summary of interviewees.

Table 5. Generated CNAP.

	Required Carbon Neutrality Actions										
Required Actions	1. New buildings are 25% more energy efficient than what is required by law.		2. Heated square meters per resident/worker will not increase in new buildings.	3. The share of grid-supplied electricity for non-district heating buildings will be decreased to 40%. The remaining share will be produced by buildings-based renewable energy. Oil-based heating will be eliminated.		4. Heating demand for building stock will decrease by 3% annually.		5. Electricity consumption for non-heating purposes will be decreased by 50% per resident/worker.		6. 20% of the remaining share of electricity consumption for non-heating purposes will be covered by own electrcity production.	7. 20% of the distrcit heating will be provided from waste- and geothermal heat, 40% from biomass, and 40% from waste combustion. Oil, coal, natural gas, peat, and plastic waste will not be combusted.
	Defined Processess and Process Owners										
Process owner for direct process for the action											Municipal district heating company (Vantaan Energia)
Direct process for the action											Vantaan Energia increases the utilization of renewable energy and develops waste combustion.
Process owner for indirect process for the action			Department of Building Control							Department of City Planning	Real Estate Center and Environmental Center
Indirect process for the required action			Department of Building Control guides constructors for efficient use of space.							City Plan requirements support production of renewable energy.	Renewable energy city assessment will be performed with the focus on geothemal and waste heat sources.
Process owner for indirect general process related to the action	Environmental Center, Information Center for Climate Actions	Department of City Planning		Environmental Center, Information Center for Climate Actions	Department of City Planning	Environmental Center, Information Center for Climate Actions	Department of City Planning	Environmental Center, Information Center for Climate Actions	Department of City Planning		
Indirect general process related to the action	The service provided by the Information Center for Climate Actions will be marketed, utilized and steered actively. Its permormance monitoring and measuring will be developed.	Climate impacts will be assessed in all the City plans where relevant.		The service provided by the Information Center for Climate Actions will be marketed, utilized and steered actively. Its permormance monitoring and measuring will be developed.	Climate impacts will be assessed in all the City plans, where relevant.	The service provided by the Information Center for Climate Actions will be marketed, utilized and steered actively. Its permormance monitoring and measuring will be developed.	Climate impacts will be assessed in all the City plans, where relevant.	The service provided by the Information Center for Climate Actions will be marketed, utilized and steered actively. Its permormance monitoring and measuring will be developed.	Climate impacts will be assessed in all the City plans, where relevant.		

3. Results

It was identified that most of the carbon neutrality actions are outside of the City's jurisdiction, limiting its capability to ensure the achievement of a carbon-neutral city. The approach currently followed by the City can potentially ensure 30% of complete GHG reductions and 58% of energy sector-related GHG emissions by eliminating GHG emissions from local district heat production. The rest of the GHG emission reductions are outsourced to the private sector or the state. The City does not allocate its own electricity production within scopes 1 or 2 for itself, thus limiting its capability to take responsibility for achieving carbon-neutral city status. The detailed results presented in this chapter are separated into two parts. First, the generated CNAP is presented, followed by validation results of the generated CNAP.

3.1. Generated CNAP

Based on the process description and the carbon neutral generation literature, a CNAP with actions, processes, and process owners was created, as presented in Table 5. The required actions for carbon neutrality are listed on top, with process owners together with direct processes in relation to required actions identified below. These could be stated as mandatory processes. Next are indirect processes and process owners, respectively. These are rather suggestive processes, and are not mandatory. This is followed by general indirect processes and process owners, which do not have any direct link to the required actions, but may have some influence over them.

3.2. Validation Results

Interviewees raised the notifications as presented in Table 6 for each action.

Table 6. Notifications for actions in CNAP.

1.	New buildings are 25% more energy efficient than what is required by law.	Several interviewees stated that the City has a plan to implement requirements for low energy buildings in all City plans, which would make this action executable. However, it was confirmed that this is not yet an official plan, as understanding this action's requirements will evolve over time.
2.	Heated square meters per resident or worker will not increase in new buildings.	Confirmed as it was presented. Not required, but a guiding action.
3.	The share of grid-supplied electricity for non-district heating buildings will be decreased to 40%. Remaining share will be produced by own renewable energy. Oil-based heating will be eliminated.	Plan includes direct requirements for City-owned buildings. For other buildings, guiding actions but no direct requirements are stated.
4.	Heating demand for building stock will decrease by 3% annually.	Confirmed as it was presented. Pointed out that it is really difficult to execute for general building stock.
5.	Electricity consumption for non-heating purposes will be decreased by 50% per resident or worker.	Confirmed as it was presented. Pointed out that it is really difficult to execute for general building stock.
6.	20 % of the remaining share of electricity consumption for non-heating purposes will be covered by building-based electricity production.	Confirmed as it was presented. Pointed out that it is really difficult to execute for general building stock. Guidance for distributed renewable energy production is planned.
7.	20 % of the district heating will be provided from waste heat, 40% from biomass, and 40% from waste combustion. Oil, coal, natural gas, peat, or plastic waste will not be combusted.	Interviewees in the City organization stated that the local energy company has committed to execute the action. However, a local energy company representative confirmed that there is no exact process for how to execute the action.

In addition, the following general comments were raised:

- Large-scale energy efficiency improvements in the existing building stock are hard, although in some building permit and City plan cases this can be required.
- The role of the state is seen as important when radical carbon emission decreases are targeted.

CNAP validation confirms the City's general carbon-neutral generation approach outlined by the generated CNAP. Table 5 shows that the only direct process, which can be mandatory by nature, is the process of local district heating. The importance of this is high, as it represented 30% of carbon emissions in 2016, as shown in Table 1. The share of energy sector emissions is 58%. However, where the local energy company is seen to be committed to the achievement of this goal by the municipal organization, it was not seen as clear from the local energy company perspective. The company does have a vision of this, but it lacks the exact execution plan, as the focus is based more on the short and medium term. The vision includes some actions that remain are highly uncertain, and so continuous planning is needed and uncertainties will exist. Additionally, for the remaining share, there are no direct processes or requirements which could be stated as mandatory. Indirect (and suggestive by their nature) processes are identified for required actions 2, 6, and 7. The Department of Building Control guides constructors toward the efficient use of space in order to restrict the built square meters. The Department of City Planning is generating and updating City plans to support renewable energy production in order to gain the necessary amount of renewable energy production via the buildings themselves. In addition, a renewable city assessment is planned by the Real Estate Center and the Environmental Center to assist in the increased share of renewable energy in both centralized and distributed generation. For other required buildings-related actions, there are no direct or indirect processes linked to them. Two general processes are planned that could partly assist in carrying the required actions: 1. The service provided by the Information Center for Climate Actions will be marketed, utilized, and steered actively. Its performance monitoring and measuring will be developed, and 2. Climate impacts will be assessed in all the City plans, where relevant. Only building stock-related processes are mandatory for the City's own buildings. Their role in carbon emissions is still marginal, below 0.5%. Indirect processes guiding the development were identified only for actions 2 and 6. For the rest of the actions there were only indirect general processes identified that were related to them. Thus, the actual efficiency of the CNAP as such is not strong. The City's primary approach is to eliminate GHG emissions from district heating production, majorly decrease the consumption of electricity by individuals and the private sector, and rely on the hope that GHG emissions from electricity production will be dramatically decreased at the national level.

4. Discussion

The results showed that in terms of the number of processes, the City's general approach to the achievement of carbon-neutral city status is mostly through decreasing consumption, focusing heavily on the energy efficiency of the building stock together with distributed renewable energy production. Most of the processes are not mandatory, thus limiting the City's capability to steer the generation. The only mandatory process related to the production perspective is centralized district heating energy production, which is owned by the City, and thus within its jurisdiction. This process potentially eliminates carbon emissions occurring as a result of such energy production. The carbon decrease potential of district heat production represented 30% of the City's total carbon emissions in 2016 and 58% of the energy sector's GHG emissions. The consumption of electricity represents 22% of the City's total carbon emissions in 2016 and 42% of energy sector's GHG emissions. The amount of electricity produced by CHP was 33% of this. This electricity production is not allocated to the City. If it were, the City's GHG emissions would initially increase, but it would increase its potential for carbon reduction measures.

Whereas the allocation of scope 1 emissions and GHG emissions from local municipal electricity production to the City is simple to justify, although not done here, GHG emissions from Scope 2 energy production have to be considered more on a case-by-case basis. Where carbon credits or compensation are offered from various sources, potentially allowing such affordable allocations to be made, one has to be aware of whether the allocation of such can be justified for carbon accounting. The municipal energy company owns shares in renewable electricity production sites.

Although electricity is purchased from the markets, the allocation of such electricity production to the City can be justified, as investments in such energy production has been decided upon by the municipality. When co-owned electricity production is included, the share of municipality-produced electricity rises to 74%. Co-owned production is completely renewable. Thus, when co-owned production shares are allocated to the City, municipal processes mean the City is 89% carbon-free from an energy sector perspective.

Even though the C40 Cities carbon-neutral city definition [23] allows such allocation of out-of-city-boundary energy production, the City has not recognized this. Centralized electricity production is seen as an out-of-city-boundary and energy production company matter influencing City emissions through the grid emission implications.

Limiting the City's boundary from electricity production increases the responsibility of external parties and limits the City's capability to achieve carbon-neutral city status. Thus, the responsibility of a truly carbon-neutral city is shifted to the energy industry and central government. Additionally, private sector energy efficiency and distributed renewable energy production measures are indirect and instructive in limiting the influence of the City's direct and mandatory measures to −58% from stationary energy system carbon emissions in 2016. It is thus seen that the major responsibility to ensure carbon neutrality belongs to central government, international organizations, the energy production sector, and real estate owners.

From the municipal organization perspective, this finding is in line with former research. Sperling et al. [3] found the need for central coordination in municipal energy planning activities in Denmark. Nilsson et al. [4] argued that municipal energy plan goals can be rather vague. Nystedt et al. [6] highlighted the importance of legislation in the energy-efficient city.

On the other hand, a willingness to adapt different approaches for the achievement of carbon-neutral city status, when these measures can be justified, was identified in this study. Similarly, Madlener and Sunak [9], for example, suggested that urban planning will be pivotal for a sustainable energy future. Studies within this field concern urban energy planning and integrating it more into existing urban planning processes. Research regarding the process of achieving absolute carbon-neutral city status is still lacking, which might partly contribute to the lack of execution plans for carbon-neutral cities and the allocation of centralized electricity production for cities. The allocation of such energy production for cities might be the only tool some cities have for achieving carbon-neutral city status. In most cases, it can be assumed that this also means the allocation of energy production beyond the physical city boundaries.

As cities' approaches toward carbon reduction have been seen to be more bottom-up in the literature, focusing on increasing the energy efficiency of buildings and integrating distributed renewable energy production, this case study city's approach was similar, with its limited control over securing the production of carbon-free energy. When developing a truly carbon-neutral city, one has to focus on net-energy flows and their emissions. Thus, it could be proposed that an efficient approach to reaching such a status and ensuring an efficient transition toward it should combine both bottom-up and top-down approaches. As a result, consumption-based energy efficiency measures would be taken into account in parallel when securing the transition to carbon-free energy production. For cities, this means that shares in energy production investments would be included in CNAP, with this production allocated to the City. Where this is not reasonable, proven annual carbon compensation mechanisms should be included to make sure that the annual net-carbon balance is zero or negative, regardless of the actual capability to shift toward complete net-zero emissions. For transparent statistics and carbon accounting, allocated energy production should be separated in the statistics so that actual carbon emissions can be calculated for the sectors and cities. Without this separation, double counting will exist. When considering cities such as Espoo, Vantaa, Tampere, Turku, and Copenhagen achieving carbon neutrality prior to national carbon neutrality, the importance of out-of-city-boundary energy investments and allocations can be seen as necessary. Even for those cities achieving carbon neutrality after it is achieved nationally, such investments are likely to be mandatory if consumption-based carbon accounting is added and/or compensation is needed.

There are certain limitations in this study which should be noted when drawing final conclusions. First, the study used the required actions for carbon neutrality prepared by the City as they are. Thus, where these actions are potentially incorrect for achieving carbon-neutral city status, the study repeats this error. Secondly, all the indirect measures and their potential were excluded from the study, underestimating the potential of the City from this perspective. On the other hand, the study also excluded the shares of future energy sector-based GHG emissions and the potential currently within GHG emissions from segments other than the energy sector—most importantly, the future electricity consumption within the transportation sector. Whilst the transportation sector is the second-highest GHG emitting sector for the City, and its electricity consumption will most likely increase dramatically, the City's capability to take responsibility for the carbon-neutral city status increases, as it can react to this consumption increase with additional carbon neutral electricity production. Thirdly, the assessment follows scenarios and assumptions of the future, which weakens the reliability of the study.

In addition, the municipal energy system is highly interlinked with waste disposal. Thus, changes in waste supply have a direct influence on energy systems. Anaerobic digestion of waste food, for instance, would offer great potential for further synergy between these sectors [42,43].

The study included only energy-sector GHG emissions, which doesn't represent the complete carbon emissions of the City. The share of energy sector GHG emissions is 52% of total GHG emissions. As stated earlier, the remaining share is dominated by emissions from the transportation sector. As the remaining carbon emission sources are seen to move more into the energy sector, this increases the potential of municipalities to take responsibility for the carbon-neutral built environment—that is, as long as centralized electricity production is allocated to the City and seen as a tool that the City can utilize and take responsibility for. Similarly, when changing carbon accounting to a consumption-based approach, the City's GHG emissions would probably increase significantly. Thus, it would be natural for the City to also compensate these GHG emissions through securing carbon-free energy production within a larger system. Doing so within the national or Scope 2 boundary would be relatively simple. To compensate global or Scope 3 GHG emissions, appropriate shares in related energy production funds could be considered, for example. Where this paper studied a reference year, it is important to recognize that system changes are rather dynamic, changing annually and influencing the potential for how carbon neutrality could be achieved. Similarly, while the shares of fossil fuels are decreasing, consumption from grid-supplied energy systems is likely to increase, which changes the carbon neutrality requirements accordingly.

5. Conclusions

As the capability of cities to impact actual radical carbon mitigation has been questioned, and with some cities having set carbon neutrality targets prior to national- or state-level targets being set, this study evaluated the options a progressive city has in order to reach energy sector-related carbon neutrality, regardless of national actions. It was identified that the city under assessment took only partial control of the drive to achieving carbon-neutral city status. Rather defined measures were more suggestive and promoted energy efficiency and distributed renewable energy production in the built environment. Actions within the City's jurisdiction were directed at municipal district heating production and the municipal building stock. These represent 30% of total carbon emissions and 58% of grid-supplied energy system carbon emissions. It was seen that a mandatory requirement to create a truly carbon neutral built environment, including the private sector, is the responsibility of central government, the energy sector and the real estate sector. The most important finding was that the City administration does not allocate its electricity production to itself, although it is owned by the

City's energy company or even completely produced within Scope 1. This excludes significant carbon reduction potential and limits the municipal organization's capability to take complete responsibility for the achievement of carbon-neutral city status from the stationary energy perspective. Thus, it is proposed that in municipal carbon accounting, municipal energy production from all scopes should be allocated to the City, and other cities aiming for carbon neutrality should consider making energy investments within and beyond their boundaries as one of the central methods to reach this target, and scope definition in carbon neutrality should justify this more clearly.

Author Contributions: Conceptualization: J.L. and S.J.; main responsibility: J.L.; supervision and writing: J.H. and S.J. All authors have read and agreed the published version of the manuscript.

Funding: This research was funded by Business Finland, 601/31/2017 and Helsinki-Uusimaa Regional Council, UIR026.

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

References

1. IEA (The International Energy Agency). *World Energy Outlook 2008*; OECD/IEA: Paris, France, 2008; p. 569. ISBN 978-92-64-04560-6.
2. Bruckner, T.I.A.; Bashmakov, Y.; Mulugetta, H.; Chum, A.; de la Vega Navarro, J.; Edmonds, A.; Faaij, B.; Fungtammasan, A.; Garg, E.; Hertwich, D.; et al. Energy Systems. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Edenhofer, O.R., Pichs-Madruga, Y., Sokona, E., Farahani, S., Kadner, K., Seyboth, A., Adler, I., Baum, S., Brunner, P., Eickemeier, B., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014.
3. Sperling, K.; Hvelplund, F.; Mathiesen, B.V. Centralisation and decentralisation in strategic municipal energy planning in Denmark. *Energy Policy* **2011**, *39*, 1338–1351. [CrossRef]
4. Nilsson, J.S.; Mårtensson, A. Municipal energy-planning and development of local energy-systems. *Appl. Energy* **2003**, *76*, 179–187. [CrossRef]
5. Vandevyvere, H.; Stremke, S. Urban planning for a renewable energy future: Methodological challenges and opportunities from a design perspective. *Sustainability* **2012**, *4*, 1309–1328. [CrossRef]
6. Nystedt, Å.; Sepponen, M. Development of a Concept for Ecological City Planning for St. Petersburg Russia. In Proceedings of the World Renewable Energy Congress-Sweden, Linköping, Sweden, 8–13 May 2011; Linköping University Electronic Press: Linköping, Sweden, 2011; pp. 3074–3081.
7. Torabi Moghadam, S.; Delmastro, C.; Corgnati, S.P.; Lombardi, P. Urban energy planning procedure for sustainable development in the built environment: A review of available spatial approaches. *J. Clean. Prod.* **2017**, *165*, 811–827. [CrossRef]
8. Stoeglehner, G.; Niemetz, N.; Kettl, K.H. Spatial dimensions of sustainable energy systems: New visions for integrated spatial and energy planning. *Energy Sustain. Soc.* **2011**, *1*, 2. [CrossRef]
9. Madlener, R.; Sunak, Y. Impacts of urbanization on urban structures and energy demand: What can we learn for urban energy planning and urbanization management? *Sustain. Cities Soc.* **2011**, *1*, 45–53. [CrossRef]
10. Park, H.; Andrews, C. City Planning and Energy Use. In *Encyclopedia of Energy*; Cleveland, C.J., Ed.; Elsevier: New York, NY, USA, 2004; pp. 317–330.
11. Mathiesen, B.V.; Lund, H.; Connolly, D.; Wenzel, H.; Østergaard, P.A.; Möller, B.; Nielsen, S.; Ridjan, I.; Karnøe, P.; Sperling, K.; et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. *Appl. Energy* **2015**, *145*, 139–154. [CrossRef]
12. Hedman, Å. *Energy-Efficient City Planning: The Role and Importance of Actionable Regulations*; Aalto University: Aalto, Finland, 2016; ISBN 978-952-60-6622-6.
13. Yoon, J.J.; Joo, Y.G.; Seungil, L. Evaluating integrated land use and transport strategies in the urban regeneration projects toward sustainable urban structure: Case studies of Hafen City in Germany and Shinagawa Station in Tokyo. *Int. J. Urban Sci.* **2011**, *15*, 187–199. [CrossRef]
14. City of New York. OneNYC 2050. Available online: https://onenyc.cityofnewyork.us (accessed on 12 December 2019).

15. City of Stockholm. Strategy for a Fossil-fuel Free Stockholm by 2040. Available online: https://international.stockholm.se/globalassets/rapporter/strategy-for-a-fossil-fuel-free-stockholm-by-2040.pdf (accessed on 12 December 2019).
16. City of Berlin. Climate-Neutral Berlin 2050. Available online: https://www.berlin.de/senuvk/klimaschutz/politik/en/ziele.shtml (accessed on 12 December 2019).
17. City of London. Zero Carbon London. Available online: https://www.london.gov.uk/what-we-do/environment/climate-change/zero-carbon-london (accessed on 12 December 2019).
18. City of Copenhagen. Carbon Neutral Capital. Available online: https://international.kk.dk/artikel/carbon-neutral-capital (accessed on 12 December 2019).
19. C40 Cities. C40 Cities. Available online: https://www.c40.org (accessed on 14 December 2019).
20. Covenant of Mayors. Available online: https://www.covenantofmayors.eu/ (accessed on 14 December 2019).
21. ICLEI. ICLEI—Local Governments for Sustainability. Available online: https://www.iclei.org (accessed on 14 December 2019).
22. GHGProtocol. Greenhouse Gas Protocol. Available online: https://ghgprotocol.org (accessed on 14 December 2019).
23. C40 Cities. Defining Carbon Neutrality for Cities & Managing Residual Emissions—Cities' Perspective & Guidance. Available online: https://c40-production-images.s3.amazonaws.com/researches/images/76_Carbon_neutrality_guidance_for_cities_20190422.original.pdf?1555946416 (accessed on 14 December 2019).
24. City of Helsinki. Hiilineutraali Helsinki 2035 -Toimenpideohjelma. Available online: https://www.hel.fi/static/liitteet/kaupunkiymparisto/julkaisut/julkaisut/HNH-2035-toimenpideohjelma.pdf (accessed on 17 December 2019).
25. City of Espoo. Tavoitteena Hiilineutraali Espoo 2030. Available online: https://www.espoo.fi/fi-FI/Asuminen_ja_ymparisto/Kestava_kehitys/Ilmastotavoitteet (accessed on 17 December 2019).
26. City of Vantaa. Hiilineutraali Vantaa 2030. Available online: https://www.vantaa.fi/asuminen_ja_ymparisto/ymparistopalvelut/resurssiviisas_vantaa/vantaan_ilmastotyo (accessed on 17 December 2019).
27. City of Tampere. Ympäristöpolitiikka ja Ilmastotavoitteet. Available online: https://www.tampere.fi/asuminen-ja-ymparisto/ymparisto-ja-luonto/kestava-kehitys/ymparistopolitiikka-ja-ilmastotavoitteet.html (accessed on 17 December 2019).
28. City of Turku. Hiilineutraali Turku. Available online: https://www.turku.fi/hiilineutraaliturku (accessed on 17 December 2019).
29. City of Oulu. Kasvihuonekaasupäästöt Oulussa. Available online: https://www.ouka.fi/oulu/ilmasto/kasvihuonekaasupaastot (accessed on 17 December 2019).
30. Finnish Government. Carbon Neutral Finland that Protects Biodiversity. Available online: https://valtioneuvosto.fi/en/rinne/government-programme/carbon-neutral-finland-that-protects-biodiversity (accessed on 17 December 2019).
31. City of Vantaa. Vantaa in Brief. Available online: https://www.vantaa.fi/administration_and_economy/vantaa_information/vantaa_in_brief (accessed on 1 December 2019).
32. City of Vantaa. Energy Consumption Statistics. Available online: https://www.vantaa.fi/hallinto_ja_talous/tietoa_vantaasta/tilastot_ja_tutkimukset/muut_tilastot_ja_tietokannat (accessed on 1 December 2019).
33. Hiilineutraali Vantaa 2030 Selvitys Tarvittavista Lisätoimenpiteistä. Available online: https://www.vantaa.fi/instancedata/prime_product_julkaisu/vantaa/embeds/vantaawwwstructure/138291_Hiilineutraali_Vantaa_2030_-selvitys.pdf (accessed on 1 December 2019).
34. Finnish Energy Industries. Statistics 2016. Available online: https://energia.fi/en/news_and_publications/statistics (accessed on 20 December 2019).
35. Vantaan Energia. Annual Report 2016. Available online: https://s3-eu-west-1.amazonaws.com/vantaanenergia/uploads/20170419133222/VE-tilinpaatos-2016.pdf (accessed on 20 December 2019).
36. Statistics Finland. Statistics 2016. Available online: https://www.stat.fi/til/salatuo/tau_en.html (accessed on 20 December 2019).
37. City of Vantaa. Resurssiviisauden Tiekartta. Available online: https://www.vantaa.fi/instancedata/prime_product_julkaisu/vantaa/embeds/vantaawwwstructure/140089_ResurssiviisaudenTiekartta-18.6.2018-final.pdf (accessed on 17 December 2019).

38. City of Vantaa. Maankäytön, Rakentamisen ja Ympäristön Toimialan Toteutussuunnitelma Vantaan Kaupungin Resurssiviisauden Tiekartan Tavoitteiden Toteuttamiseksi 2018–2021. Available online: https://www.vantaa.fi/instancedata/prime_product_julkaisu/vantaa/embeds/vantaawwwstructure/144821_ResurssiviisaudenTiekartta-Mato-19032019.pdf (accessed on 17 December 2019).
39. Leech, B.L. Asking Questions: Techniques for Semistructured Interviews. *Political Sci. Politics* **2002**, *35*, 665–668. [CrossRef]
40. Spradley, J.P. *The Ethnographic Interview 1979*; Holt, Rinehart and Winston: New York, NY, USA, 1979.
41. McCracken, G. *The Long Interview 1988*; Sage: Newbury Park, CA, USA, 1988.
42. Bartocci, P.; Zampilli, M.; Liberti, F.; Pistolesi, V.; Massoli, S.; Bidini, G.; Fantozzi, F. LCA analysis of food waste co-digestion. *Sci. Total Environ.* **2020**, *709*, 136187. [CrossRef] [PubMed]
43. Huiru, Z.; Yunjun, Y.; Liberti, F.; Bartocci, P.; Fantozzi, F. Technical and economic feasibility analysis of an anaerobic digestion plant fed with canteen food waste. *Energy Convers. Manag.* **2019**, *180*, 938–948. [CrossRef]

Aalto-DD 25/2021

9 789526 402826

ISBN 978-952-64-0282-6 (printed)
ISBN 978-952-64-0283-3 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)

Aalto University
School of Engineering
Department of Built Environment
www.aalto.fi

BUSINESS +
ECONOMY

ART +
DESIGN +
ARCHITECTURE

SCIENCE +
TECHNOLOGY

CROSSOVER

DOCTORAL
DISSERTATIONS