Department of Mechanical Engineering

Advancing sustainable transformation of cities

An analysis of city and household level efforts in the pursuit of carbon-neutrality targets

Hannele Ahvenniemi

Aalto University

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Hannele Ahvenniemi

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Abstract

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Abstract
It has been widely recognised that cities and particularly the built environment have a major role in fighting against climate change. Acknowledging the challenge, city governments have been eager to declare ambitious carbon-neutrality targets along with smart city strategies. Simultaneously academia and the business sector have announced a number of measures and solutions as to how these targets can be reached. However, a commonly accepted definition on smart cities – and an understanding of the link to sustainable cities – is still lacking. High expectations are also faced by households, major contributors of cities' greenhouse gas emissions, who are expected to be motivated to adopt smart and sustainable measures and understand the significance of them.
This dissertation composes of five individual studies examining the topic 'Advancing sustainable transformation of cities' from various angles and on both city and household levels. The first part of the dissertation focuses on the target setting of cities, studying 1) the similarities and differences of smart and sustainable city targets, and 2) how cities express their environmental sustainability targets in their strategies. The second part of the dissertation deals with the household level, studying the environmental impacts and economic benefits of sustainability measures implemented by households, as well as other motivational factors behind sustainable choices.
The results of the publications show that advancing environmental sustainability efficiently on both city and household levels may be challenging. When cities aim for 'smartness', they do not automatically pursue environmental sustainability. It seems that remarkable efforts are still needed to incorporate environmental sustainability targets of cities to an all-compassing action plan. When households implement carbon mitigating actions, these actions may not always lead to efficient results, nor do they necessarily provide economic benefits. Forerunner households who have implemented renewable energy technologies however report other type of benefits: they experience pleasure from energy self-sufficiency and being able to share information, among others. Information is crucial regarding households' efforts to cut carbon by implementing actions, and smart technologies may play a key role here. While smartness targets have become pervasive – bringing along technologies and measures to speed up sustainable transformation – it is essential for cities to clarify which of the smart measures truly are useful in regard of environmental sustainability goals.

Keywords sustainable city, smart city, household energy, renewable energy, carbon mitigation, cost impact, household energy behaviour

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Tiivistelmä

Tekijä
Hannele Ahvenniemi

Väitöskirjan nimi
Kaupunkien kestävyystavoitteiden edistäminen – Hiilineutraaliustavoitteita edistävien menettelyjen tarkastelu kaupunkien sekä kotitalouksien tasolla

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Tiivistelmä
Kaupunkien sekä rakennetun ympäristön suuri merkitys ilmastonmuutoksen vastaisessa taistelussa on tunnistettu laajasti. Tarttuakseen haasteeesen, kaupungit ovat julistaneet kunnianhimoisia hiilineutraaliustavoitteita sekä julkaisseet 'smart city' (älykkään kaupungin) strategioita. Samaan aikaan useat eri tahot ovat tarjonneet lukuisia keinoja ja ratkaisuja tavoitteiden saavuttamiseksi. Laajasti hyväksyttyä määritelmää älykkäille kaupungeille – eikä myöskään ymmärrystä linkittymisestä kestävän kaupungin käsitteeseen – ei kuitenkaan edelleenkään ole. Kovia odotuksia kohdistuu myös kotitalouksiin, joiden toiminta aiheuttaa merkittävän osuuden kaupunkien kasvihuonekaasupäästöistä: kotitalouksien odoteetaan olevan motivoituneita ottamaan käyttöön kestäviä sekä 'älykkäitä' keinoja ymmärtäen myös näiden vaikutuksen.

Tämä väitöskirja koostuu viidestä erillisestä tutkimuksesta, jotka kaikki tarkastelevat kaupunkien kestävyystavoitteiden saavuttamista eri näkökulmista, sekä kaupungin että kotitalouksien tasolla. Ensimmäinen osa keskittyy kaupunkien tavoiteasetantaan tarkastellen 1) ekologisesti kesävien sekä älykkäiden kaupunkien eroja ja yhtäläisyyksiä, ja 2) kuinka kaupungit ilmaisevat ympäristötavoitteita strategioissaan. Väitöskirjan toinen osa käsittelee kotitalouksia, tarkastellen kotitalouksien vähähiilisyystoimenpiteiden ympäristövaikutuksia ja taloudellisia hyötyjä, sekä myös muita motivaatiotekijöitä valintojen takana.

Tulokset osoittavat, että ekologisen kestävyyden tehokas edistäminen sekä kaupunkien että kotitaloukisen tasolla voi olla haastavaa. Kun kaupungit pyrkivät olemaan 'älykkäitä', ne eivät välttämättä samalla tavoittele ekologista kestävyyttä. Merkittäviä ponnisteluja siis tarvitaan, jotta ympäristötavoitteet saataisiin laajemmin osaksi kaupunkien toimenpidesuunnitelmia. Kun kotitaloudet puolestaan tekevät valintoja pienentääkseen hiilijalanjälkeä, nämä toimenpiteet eivät välttämättä johda merkittäviin tuloksiin, eivätkä ne aina tarjoa kotitaloudelle taloudellisia hyötyjä. Uusiutuvaa energiaa hyödyntävät edelläkävijäkotitaloudet sen sijaan raportoivat muunlaisia koettuja hyötyjä: he kokevat iloa muun muassa energiaomavaraisuudesta ja siitä, että voivat tarjota informaaatiota muille. Informaatiolla on keskeinen merkitys hiilineutraaliustavoitteiden saavuttamisessa, ja älykkäät teknologiat voivat olla hyödyksi tässä. Siinä missä älykkyystavoitteet ovat keskeisessä roolissa kaupungeissa – tarkoituksena tuoda yhteen erilaisia teknologioita ja keinoja kestävyystavoitteiden edistämiseksi – on kuitenkin tärkeää, että kaupungit selventävät, mitkä näistä toimenpiteistä voivat todella olla hyödyksi ympäristötavoitteiden saavuttamisessa.

Avainsanat kestävä kaupunki, älykäs kaupunki, kotitalouksien energiankäyttö, uusiutuva energia, hiilijalanjäljen pienentäminen, kustannusvaikutukset

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Helsinki, 20 November 2020
Hannele Ahvenniemi

Contents

List of Publications

This dissertation consists of a summary report and the following original publications which are referred to in the text as Publications I to V. The publications are reproduced with kind permission from the publishers.

I: Ahvenniemi, Hannele; Huovila, Aapo; Pinto-Seppä, Isabel; Airaksinen, Miimu. 2017. What are the differences between smart and sustainable cities? Cities, volume, 60A, pages 234-245. https://doi.org/10.1016/j.cities.2016.09.009.

II: Ahvenniemi, Hannele; Huovila, Aapo. 2020. How do cities promote urban sustainability and smartness? An evaluation of the city strategies of six largest Finnish cities. Environment, Development and Sustainability. https://doi.org/10.1007/s10668-020-00765-3.

III: Ahvenniemi, Hannele; Häkkinen, Tarja. 2020. Households' potential to decrease their environmental impacts: A cost-efficiency analysis of carbon saving measures. International Journal of Energy Sector Management, volume 14, issue 1, pages 193-212. https://doi.org/10.1108/IJESM-02-2019-0009.

IV: Ahvenniemi, Hannele; Pennanen, Kyösti; Knuuti, Antti; Arvola, Anne; Viitanen, Kauko. 2018. Impact of infill development on prices of existing apartments in Finnish urban neighbourhoods. International Journal of Strategic Property Management, volume 22, issue 3, pages 157-167. https://doi.org/10.3846/ijspm.2018.1540.

V: Karjalainen, Sami; Ahvenniemi, Hannele. 2019. Pleasure is the profit - The adoption of solar PV systems by households in Finland. Renewable Energy, volume 133, pages 44-52. https://doi.org/10.1016/j.renene.2018.10.011.

Author's Contribution

The author was the first and corresponding author in four publications, the research of which was done together with the co-authors but under supervision and planning by the author. In one of the publications the author contributed as the second author.

Hannele Ahvenniemi is the primary author of **Publication I.** The publication was initiated by the author together with Dr. Miimu Airaksinen, who also had a supervising role along the process. Planning the methodology and conducting the analysis was carried out by the first author together with doctoral candidate Aapo Huovila, who also contributed largely to the literature review. Dr. Isabel Pinto-Seppä participated by commenting on the manuscript during the writing process.

Hannele Ahvenniemi is the primary author of **Publication II.** The publication was initiated by the first author, and the research, including research design, conducting the studies and analysing the results, was executed mainly by the first author. Aapo Huovila participated in formulating the methodology and also provided feedback in conducting the analysis. Aapo Huovila also assisted in writing the literature review as well as commented on the manuscript during the writing and review process.

Hannele Ahvenniemi is the primary author of **Publication III.** The publication was initiated by the author together with Dr. Tarja Häkkinen, who also had an important role in formulating the research design and in commenting on the manuscript during the writing and review process. The first author had a major role throughout the writing process in research design, literature review, conducting the analysis and in analysing the results.

Hannele Ahvenniemi is the primary author of **Publication IV** and had a major role throughout the research and writing process**.** The publication was initiated together by the author and M.Sc. (Tech.) Antti Knuuti who also contributed to the research design and in processing of the research data. Formulating the method was done by the author but with the help of Prof. Kauko Viitanen, Dr. Kyösti Pennanen and Dr. Anne Arvola. The statistical analysis was conducted and analysed by the first author. The co-authors participated by giving feedback on the writing and review process.

Hannele Ahvenniemi is the second author of **Publication V.** The publication was initiated together with Dr. Sami Karjalainen who carried out the principal part of the work. The author contributed by writing most of the literature review, participating in the research design and in formulating the interview questions, carrying out one of the interviews and giving feedback during the writing process.

1. Introduction

1.1 Background

As the threats of climate change have become more evident in the 21st century, actors on international, national and local levels have been mobilised to work towards a sustainable future for the planet. By signing the Paris Agreement, 189 nations have adhered to the goal of keeping the global temperature increase of this century below 2 degrees Celsius above pre-industrial levels, and limit the temperature rise further to 1.5 degrees Celsius (United Nations Climate Change). Committing to the target, European Union, with all its member states, aim to be climate-neutral (with net-zero greenhouse gas emissions) by 2050 (European Commission).

Great expectations are placed on cities and urban areas, which can be seen as both sources and victims of climate change. Although cities cover only 2% of the surface of the earth, they are however responsible for 60-80% of the global energy consumption (Sodiq et al., 2019). According to United Nations (2019), currently 55% of world's population resides in cities and urban areas, and by 2050, this proportion is forecasted to reach 68%. The growing number of people living in cities will have to face the effects of climate change in the forms of increasing prevalence of floods, heat waves, drought, water scarcity and forest fires (EEA, 2019). It should also be noted that as hubs of human activity, cities do have high levels of energy consumption and emissions, but they also have great potential to green energy transition because of the existing resources and infrastructure (Byrne et al., 2015).

Cities worldwide have recognised the need to decrease greenhouse gas emissions, and actions have been taken by declaring ambitious carbon-neutrality targets. For example, all largest Finnish cities aim to be carbon neutral latest by 2040, some of them already by 2030. The 21st century has also evidenced the rise of the 'smart city' concept, and a great number of cities have declared their smart city strategies and missions either as part of or separately from their sustainability targets. While a commonly accepted definition of the smart city concept is still lacking, some of the technology-centric definitions highlight the role of information and communication technologies (ICT) and Internet of Things (IoT) along with automation and control systems. According to this view, technologies should be applied accross various domains of cities, making infrastructure more intelligent, interconnected and efficient and providing services for the citizens (Washburn et al., 2010; Balducci and Ferrara, 2018; Harrison et al., 2010). Many of the technology-centric definitions suggest that when ICT becomes pervasive, cities become smarter in addressing environmental problems (e.g. Bibri, 2018), and for example IoT may contribute to green transportation, energy-conservation and environment-protection (Liu, 2018). Another common perspective highlight the improved quality of life and citizen wellbeing as the target of smart cities (e.g. Fu and Zhang, 2017). Typical social sustainability targets of smart cities vary from human collaboration (Meijer and Bolivar, 2016) to human and social capital development - such as knowledge, intelligence and creativity (Angelidou et al., 2017) and citizen engagement and participation (Nam and Pardo, 2011; Balducci and Ferrara, 2018). To summarise, although a wide array of smart city definitions have been offered, many of them are in line with the definition by Fu and Zhang (2017) suggesting that while the more traditional 'sustainable cities' focus on ecological and economic aspects, the focus of 'smart cities' is on social and economic aspects.

As cities have committed to highly ambitious carbon-neutrality targets while simultaneously publishing their smart city strategies, a crucial question is, whether aiming for smart city targets may advance environmental sustainability, a question raised for example by Haarstad and Wathne (2019). The underlying assumption of this dissertation is that the main purpose of smart city goals should be to advance environmentally sustainable transition of cities and to cut greenhouse gas emissions. However, technology can, and should, provide efficient tools to reach environmental targets.

1.1.1 Cities' measures to reach their carbon-neutrality targets

Cities aim to find efficient means to reduce greenhouse gas emissions in order to reach the ambitious carbon-neutrality targets. Achieving carbon-neutrality requires both carbon emission cuts and compensation: for example the city of Helsinki aims to reach carbon neutrality by 2035 by cutting greeenhouse gas (GHG) emissions by 80% from year 1990, and the remaining 20% will be compensated by cutting emissions elsewhere or by increasing the number of carbon sinks (City of Helsinki, 2018). As buildings and construction account for about 39% and transportation for 22% of global energy-related CO_2 emissions (IEA, 2017), measures to change land use, building stock and energy systems, but also household behaviour are crucially needed. The Energy Performance of Buildings Directive (EPBD), according to which all buildings must be decarbonised by 2050 (European Commission, 2019) sets ambitious targets to the energy efficiency of buildings. Reaching of the energy efficiency targets is steered by the national building code and may be accelerated by various national level policies or support instruments (Economidou et al., 2020). Meanwhile, the possibilities of cities to speed up the sustainable transition often lies in urban planning, information guidance and in implementing low-carbon measures in their own buildings.

Typical measures to reduce GHG emissions of buildings are improving the energy efficiency to reduce operational energy demand and using renewable energy (Röck et al., 2020). Decentralised energy systems with small-scale renewable energy production have been identified as efficient in decreasing carbon emissions (Vezzoli et al., 2018). Decentralised energy production is essential in a 'Positive Energy District', which is a neighbourhood with net zero CO_2 emissions. In a Positive Energy District individual buildings may reduce their energy demand by energy efficiency measures, but in addition, combined with renewable energy systems, local energy network and energy storage, optimisation and cost-efficient solutions may be provided (European Union, 2020). Here smart techologies, enabling efficient functioning of the energy network together with decentralised supply are the key. With the help of smart grid an individual energy consumer can become an energy producer, called as 'prosumer' and participate in the electricity market (Zafar et al., 2018). The role of automation and control systems are substantial: they enable timing of energy consumption which makes it possible for buildings to participate in demand response and to increase the market share of renewable energy. This paradigm shift in which centralised power systems are being replaced with millions of smaller units has been called 'democratisation of power systems' (e.g. Zhong 2017), giving a possibility for all levels and all actors to make decisions regarding renewable energy use.

While the focus of carbon reduction targets is heavily placed on decreasing the GHG emissions from operational energy, the life cycle perspective should not be ignored. As the energy-efficiency of buildings is improving, the relevance of GHG emissions related to manufacturing and processing of the building materials is increasing (Röck et al., 2020). Constructing an energy-efficient building typically is more carbon intensive, but the lower GHG emissions of the operational phase offsetts the high initial emissions, leading to lower carbon footprint during the whole life cycle of the building (Ruuska and Häkkinen, 2015). A similar pattern may apply to other energy-reducing products and technologies, and it has been suggested that when assessing environmental impacts of applying new technologies, also the production of these technologies should be included into the assessment (ITU, 2015).

Regarding land use, cities have a possibility to steer sustainable transition through urban planning, by deciding locations for various functions (city centers, offices, residential areas etc.), hence affecting travel distances and transportation demand within the city. For example a study by Wang et al. (2018) showed that characteristics of the urban form such as high density, mixed use and accessibility to urban transit, are efficient for mitigating carbon emissions of urban areas. Cities can also encourage the use of cleaner transport by offering good public transport services and constructing non-motorised traffic routes for pedestrians and cyclists. This is also related to the compactness of the city: it is more efficient to organise public transport in a dense and compact city – and the short distances also support walking and cycling – whereas cities covering larger geographic areas are more likely to be dependent on cars (Rimi and Aliyu, 2019).

Cities can however not act alone in fighting against climate change – nor do they have the means to – and all actors need to be activated (industry, NGOs, residents etc.). Through consumption behaviour, households may be responsible for up to 72% of global GHG emissions (Dubois et al., 2019) and hence have a key role in pursuing carbon-neutrality. Thus cities should be interested in motivating households to implement environmentally sustainable actions and to actively enhance their energy behavior. For example, Creutzig et al. (2018) argue that the focus of climate change mitigation is too often on supply-side technologies, whereas more focus should be put on the demand-side. Consumption studies show an enormous saving potential of household GHG emissions: for example Bjelle et al. (2018) show a 58% reduction in carbon footprint if a household impelements a list of 34 energy saving measures (when not considering re-spending). The rise of the smart city concept has been accompanied with suggestions on how households can decrease their energy consumption with help of smart technolgies such as smart meters and on-time monitoring systems (European Commission, 2014). This information and data-centric approach is in line with motivational studies on household enegy consumption, which have largely highlighted the role of information and education (Ouyang and Hokao, 2009; Hori et al., 201; Mizobuchi and Takeuchi, 2013). Another body of literature on motivational studies emphasise the role of economic aspects and financial incentives in motivating households to take up sustainable actions (Han et al., 2013; Van Den Bergh, 2008, Mizobuchi and Takeuchi, 2013).

1.2 Scope of the dissertation

Although plenty of information is available about technical solutions to reduce carbon emissions and to reach environmental sustainability targets, knowledge of efficient means to advance this development is still lacking. The scope of the dissertation is illustrated in Figure 1, describing the decision-making levels regarding environmental target setting, and the environment in which households operate. Recognising the complexity of the sustainable transformation of cities, the research approach of this dissertation is broad, containing both city and household levels. The city level forms an indispensable level of study as cities have a manifold role in advancing urban sustainability: cities set sustainability targets for all operations of the city, they are responsible for the infrastructure, they may implement direct actions and also adopt policies to support implementation of environmentally sustainable meaures by other actors (households, business sector etc.). Households are responsible for a great share of urban carbon footprint, and therefore understanding the carbon mitigation actions from the perspecive of individual households is essential. Regarding the dual approach, it is however important to note that the city and household levels should not be considered only as separate actors because the decision makers of cities – who are responsible for planning and implementing sustainable strategies and actions – are selected by the citizens. Also ’smartness’ and its intersections with sustainability is an inseparable theme throughout the dissertation because of the increasing interest of cities to be ’smart’.

The five individual publications each examine the topic of advancing sustainable transformation of cities within their specific scope, responding to the research questions presented in Section 1.3. The first part of the dissertation operates at the city level, studying internationally used smartness and sustainability frameworks in Publication I, and focusing on the city strategies of six largest Finnish cities in Publication II. The second part deals with the household and neighbourhood levels, studying impacts of various household choices. Publication III focuses on environmental and economic impacts of various consumption scenarious of a theoretical case family, and Publication IV deals with infill development and its price impact on existing buildings in the neighbourhood. Finally, in Publication V household motivation is studied by interviewing owners of detached houses. Due to the broad and multi-level researh problem examined in the dissertation, the research approach is multidisciplinary encompassing technical and mathematical approaches but also social science perspectives.

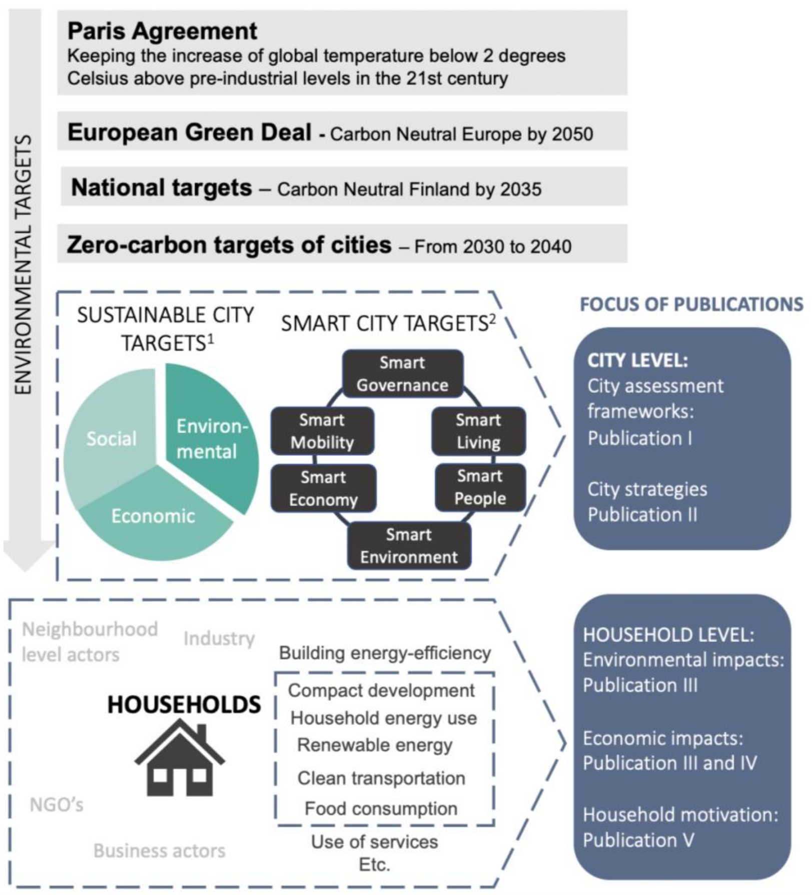

Figure 1. Objective of the dissertation and an illustration of the environment in which households operate.

[1] Sustainable city targets are based on the three dimensions of sustainability, initially introduced by World Commission on Environment and Development (WCED) (1987),

[2] The smart city targets are based on smart city characteristics suggested by Giffinger et al. (2007), which represent one example of definition of smart city dimensions.

1.3 Research questions

The overall aim of the dissertation is to increase understanding on measures to advance sustainable transformation of cities. This topic is approached by help of three sub-questions, examining urban environmental sustainability and greenhouse gas emission reduction targets from various angles and on both city and household levels. These both levels must be understood in the sustainability pursuit of cities (as explained above). The three research questions of this dissertation are presented below and summarised in Figure 2.

The first research question approaches the topic at the city level:

RQ1: How do cities advance environmental sustainability by their target setting?

This research question is addressed in Publications I and II, which both examine the targets of cities, studying the differences and similarities of ’smart cities’ and ’sustainable cities’. The aim is to understand whether pursuing smart city targets may also advance environmental sustainability. This question is crucial for understanding the state of current urban sustainability development, as ‘smart city’ targets have been strongly emphasised in the 21st century. Publication II also views the question from another angle, assessing the extent to which cities express their environmental sustainability targets in their city strategies.

The second research question views the topic at the household level and from a more practical angle:

RQ2: How can households decrease their environmental impacts effectively?

This research question is addressed in Publication III which studies households’ daily choices and their environmental and cost impacts. The actions selected for the study are all low-cost, small-scale actions, which may be implemented by any household. Information on efficient measures is essential also at the city level, as cities have an important role in motivating households to take up actions.

The third research question also views the topic from the perspective of a household and takes a motivational angle:

RQ3: In which ways can households benefit from implementing sustainable actions?

This research question aims at understanding the motivation provided for households when implementing actions which advance environmental performance of the urban built environments. Publications III, IV and V address this question with different case studies, focusing on various carbon-mitigating measures which often serve as targets of both smart and sustainable cities. These meassures are energy and food consumption and transport choices in Publication III, infill development in Publication IV and implementing photovoltaic panels (PV system) in Publication V. The publications examine household motivation from two angles. As economic benefits are often presented as an important motivational factor, Publications III and IV focus on economic impacts of actions. Acknowledging the importance of also other motivational factors, Publication V takes a purely qualitative approach aiming to capture the deeper motivation behind sustainable choices.

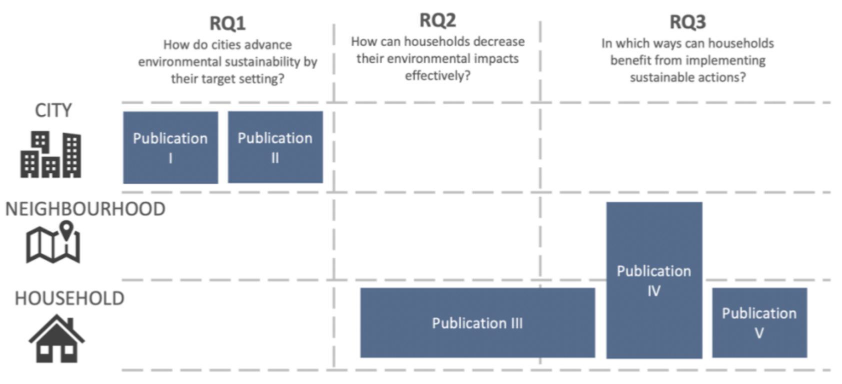

Figure 2. Research questions and scope of publications.

1.4 Structure of the dissertation

The dissertation comprises of this summary and the appended research papers, which all discuss the topic of sustainable transformation of cities from different angles and on different levels (city and household levels).

The introductory section depicted the background of the research and presented the research aim. The used methods are introduced in the following section (Section 2). Section 3 presents the summaries of the papers followed by a discussion section (Section 4) and finally the conclusions (Section 5).

2. Research methods

Due to the interdisciplinary nature of the dissertation, various methods were used to study the topics of each publication, comprising both quantitative and qualitative methods, as described in this section. The used methods for each study are summarised in Table 1.

Table 1. Methods and data used in the publications.

	Publication I	Publication II	Publication III	Publication IV	Publication V
Method	Content analysis; Statistical analysis	Content analysis	GHG emission and cost analysis	Statistical analysis	Semi-structured interviews
Data	Close to 1000 performance measure-ment indicators	City strategies	Consumption data gathered from various sources	Prices of housing transactions	Households' experiences
Cases	8 sustai-nable city and 8 smart city frameworks	6 largest Finnish cities	A theoretical case of an average Finnish household	7 case neigbour-hoods and 7 reference neighbourho ods	28 Finnish solar PV adopters

2.1 Content analysis to study the city level efforts

Publications I and II studied the similarities and differences of the 'smart city' and 'sustainable city' targets. The aim of Publication I was to examine the differences of smart city and urban sustainability frameworks, and Publication II studied the magnitude and overlapping of various sustainability and smartness goals presented in the city strategies. Both publications used a similar method, following the principles of quantitative content analysis, although the different nature of the used data required distinct types of data processing. Content analysis is "*a research technique for making replicable and valid inferences from texts (or other meaningful matter) to the contexts of their use*"

(Krippendorff, 2004). Shortly put, it enables examining large amounts of data in a systematic way, which allows identifying and clarifying topics of interest (Weber, 1990).

In Publication I the data consisted of 16 city assessment frameworks with close to 1000 indicators whereas in Publication II the city strategies of six largest Finnish cities were studied. Publication I focused on indicators which are crucial for target setting of cities and tracking and monitoring progress on performance (ISO, 2014). The difference between data/variable and an indicator is sometimes ambiguous: variable becomes an indicator only when it has a certain role in evaluation of the phenomenon (when the changes of the data can be defined as negative or positive) (Tanguay et al., 2010). Hence indicators have a crucial role in the sustainable transition of cities. In Publication II the focus was placed on city strategies which are the most significant documents summarising a city's most important targets. It is also important to note that as the city strategy is composed and implemented by the city council, which members are selected every four years by local election, its outputs should reflect the values and aspirations of the citizens.

The overall research process of Publications I and II is presented in Figure 3. In both studies the studied objects were unitised and (re)categorised to enable performing a comparison. In content analysis it is desirable to define "*the smallest units that bear all the information needed in the analysis*" (Krippendorff, 2004). In Publication I the studied objects were the indicators, which were treated as the studied units. As in Publication II, the studied data was retrieved from the city strategies, the principles of basic content analysis was followed, which typically uses existing texts, originally created by others, and for other purposes than the current research (a.k.a. secondary data) (Drisko & Maschi, 2015). Publication II studied the goals which were presented in the city strategies in literal form, and hence the text had to be decomposed into minor components (units) by identifying and recording each inidvidual goal presented in the text.

In both studies, the units were coded into explicit categories and described by using statistical tools. A deductive approach was followed, explained for example by Gheyle & Jacobs (2017), in which categories are decided in advance, based on a theory, and unambiguous coding rules are set to organise the units. The logic behind forming of the categories was similar in both Publications I and II: the units were regrouped under two (Publication I) and three (Publication II) different types of categories. One type of categorisation, used in both studies, was to divide the units under the three dimensions of sustainability (called as 'impact categories' in Publication I and 'sustainability dimensions' in Publication II). This division was initially introduced by WCED (1987) and has since been established as three pillars of sustainability (e.g. Giddings et al.

2002). The second categorisation used in both studies was to divide the units under sector categories. These categories were formed by using literature sources but adapted to better cover all functions of the cities. As the focus of Publication II was on Finnish cities, in this publication the categories were also adapted to better suit the Finnish environment. Literature sources were also used to form the third categorisation type in Publication II, which were the 'smartness aspects' (please see more details in appendix A and B).

The method for analysing the units in both publications was 'frequency count', simply counting how many of the units fall under each category. Publication I studied how many of the indicators of smart city and urban sustainability frameworks were related to each sustainability dimension and each sector. Likewise, Publication II studied how many of the goals mentioned in the city strategies were related to each sustainability dimension, smartness aspect and sector. By frequency count it was also possible to study how the categorisations overlapped with each other by examining the number of units (indicators or goals) belonging under both a specific sustainability dimension and a chosen sector (for example, a unit may fall under the environmental sustainability dimension and the transport sector).

In Publication I the statistical significance of the distribution of indicators of smart city and sustainable city frameworks was further analysed by using student's t-test. The method is explained for example by Diamantopoulos and Schlegelmilch (2000). In Publication II the focus was not placed on identifying the differences of the studied objects and therefore no similar statistical validation was needed.

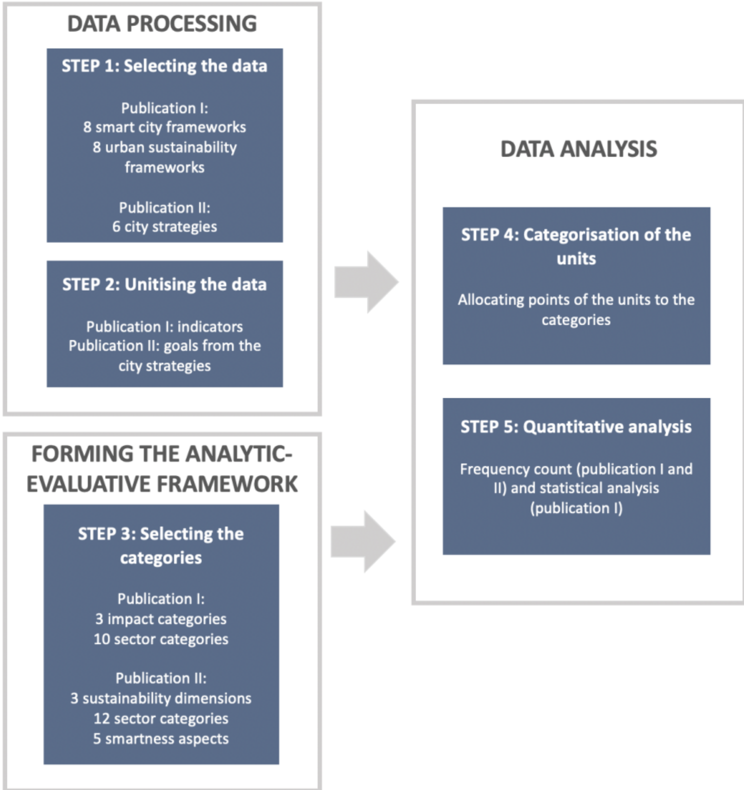

Figure 3. Research process of Publications I and II.

2.2 Household level analyses

2.2.1 GHG emission and cost analysis

Publication III assessed environmental and cost impacts of household choices. Four 'areas of living' were selected for the study: household electricity, space heating, transport and food consumption, which constitute a substantial share of household GHG emissions (Heinonen et al., 2013; Ferguson and MacLean, 2011; Tukker and Jansen, 2006). The focus was placed on everyday choices of households and on measures which any average household could implement. A three-member family residing in an apartment building in Finnish urban area was selected as the case household. To construct the baseline scenario of the case household's consumption, average consumption levels were assessed. Appropriate sources for each area of living were used: 1) energy consumption data from WinEtana programme (Kosonen & Shemeikka, 1997) developed by VTT Technical Research Center of Finland combined with electricity company data, 2) data on transport habits from the national passenger transport survey

(Finnish Transport Agency, 2018), and 3) food consumption data from the Natural Resources Institute Finland (2018).

The research process of Publication III is presented in Figure 4. The analysis was performed by composing a number of scenarios of household energy behaviour, regarding the four areas of living mentioned above. Two following selection criteria were used to determine which measures to include into the study: first, the measure should depend solely on the decision of the household, and the household should have direct control over the measure. For this reason, for example changing the heating mode of the apartment was not selected as a studied measure, as residents of Finnish apartment buildings cannot make decisions about the heating mode by themselves. Second, the measure should either be free of charge or relatively low cost, to allow implementation by any average household regardless of their income level or economic situation. The methods to assess environmental and cost impacts of the selected scenarios are presented below. The selected time span for both environmental and economic analyses was one year. Although several studies have examined the environmental impacts of various sectors of living, the authors of the publication are not aware of any similar scenario-based analyses of household choice impacts, comprising both environmental impact and cost impact analyses. The novelty of the study also lies in the comprehensive analysis of choices which are within the reach of an average household (solely depending on household's own decisions) and do not require remarkable financial investments.

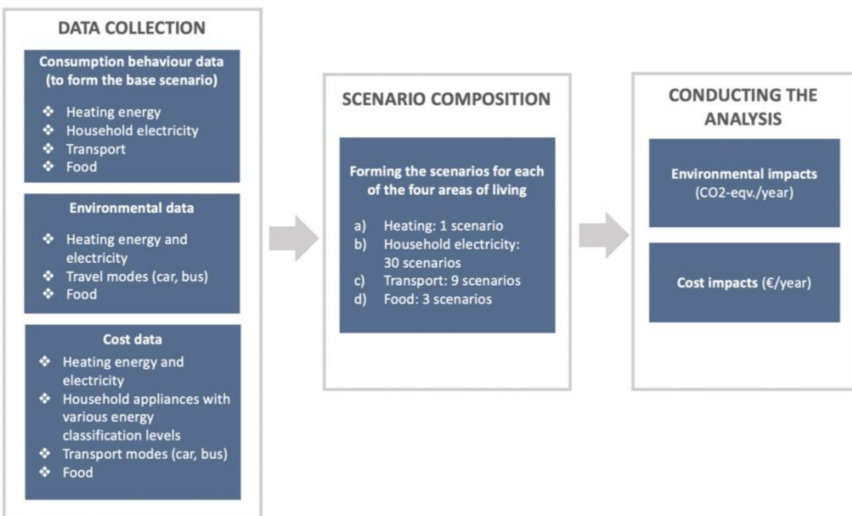

Figure 4. Research process of Publication III.

CO_2-equivalent (CO_2-eqv.) was selected to represent the environmental impact of household choices. This unit is commonly used for comparing the emissions from different greenhouse gases based on their global-warming potential (GWP) (e.g. Eurostat, 2017). The idea is that various greenhouse gases can be converted to this unit, expressing the amount of CO2 that would cause the same amount of global warming. Using CO_2-eqv. allows comparing the environmental impacts of various products or functions, as in Publication III the emissions from consumption of heating energy, household electricity, transport and food. The energy profiles used for calculations, were average Finnish electricity, 152 g CO_2-eqv./kWh, and district heating, 173 g CO_2-eqv./kWh, which are based on combined heat and power generation in Finland and imported energy in 2016, calculated by VTT Technical Research Centre of Finland (Häkkinen and Vares, 2018). It should be noted that as national averages of CO_2-eqv. from electricity and district heating were used, local variations were not considered. However, the study focused on urban areas, where the emission factors of district heating produced by the local suppliers are close to the national averages. Also, in Finland the average CO_2-eqv. of electricity is rather low compared to many other European countries (Moro and Lonza, 2018) and hence repeating the study at another geographic location would lead to different results. To calculate the CO_2-eqv. from transport modes, emission factors for car and bus were retrieved from LIPASTO database, maintained by VTT Technical Research Centre of Finland (VTT, 2017), and environmental data for fuel was retrieved from the European Life Cycle Database (ELCD) (JRC, 2018). Finally, used CO_2-eqv. values for food consumption were provided by the Finnish Environment Institute (Finnish Environment Institute).

Regarding household energy (including appliances and heating) and transport, environmental impact assessment covered only the *use stage*. It is important to note that a more holistic approach including environmental impact assessment of all life-cycle stages (for example manufacturing or end-of-life disposal of a car or demolition of housing) might have given different results. Focusing only on the use stage is however reasoned as households are not provided with sufficient information about the other stages, making it nearly impossible for households to place their decisions on these facts. In case of food consumption, however, information about the carbon impacts is available for the consumers, and in this analysis, the used environmental profiles cover the life-cycle stages until retail (including resource extraction, materials processing, manufacturing, transport).

To study the economic motivation to adopt sustainable action, assessing cost impacts of the scenarios were added to the analysis. Several studies show the importance of financial incentives and cost benefits as motivational factors behind sustainable behavior of households (e.g. Zou and Yang, 2014; Han et al., 2013). To assess the cost impacts of household choices, the following sources were used: Statistics Finland (2018) for energy and food consumption, data about sales prices of electrical appliances from a collection of appliance retailers, prices of public transport travels from public transport providers in the cities of Helsinki, Turku and Tampere and finally, data provided by the Finnish Petroleum and Biofuels Association (2018) to calculate the costs of car travels.

2.2.2 Statistical analysis

Publication IV also dealt with the household level, but the focus of the study was placed on decisions of a housing company, extending the impact also on the neighbourhood level. As compact city development has been recognised as an important means for advancing low-carbon development of cities (e.g. Glaeser and Kahn, 2010; OECD, 2012; Bibri et al., 2020), the aim of Publication IV was to assess the economic motivation provided for households - who stand behind the decisions of housing companies – when choosing to advance infill development. The potential economic benefits for households are twofold: first, the housing company (owned by individual households) can use the revenue from selling land to cover refurbishment costs (Seppälä, 2013; Kuronen et al., 2011). Second, the surrounding neighbourhood may benefit from infill development by improved services, transport options and infrastructure etc. which may, among other mechanisms, have an upward price impact on the existing apartments. The focus of this study was placed on the latter type of benefit, examining the price impact of infill development on existing apartments. It is important to note that also the city has a role in this process, as it can – by fees or zoning practices – either advance or hamper infill development.

The method used in Publication IV was purely statistical, analysing housing prices of neighbourhoods with recent infill development and comparing them to reference neighbourhoods without infill development. The analysis was based on housing transaction data from 14 neighbourhoods, during the lifespan of one decade. In total, data from more than 6000 housing transactions were used for the study. The chosen method was Difference-in-Difference (DID), which is typically used to compare the differences of two groups over a certain period of time. One of the groups (treatment group) is exposed to a treatment or intervention whereas the other (control group) is not (Deschenes and Meng, 2018). DID was applied via a hedonic regression model, which is commonly used to capture the influence that various characteristics have on housing prices (Eurostat, 2013).

The case neighbourhoods (treatment group) were selected based on four major criteria: 1) The majority of the buildings of the neighbourhood had been built between the 1960s and 1980s, 2) The neighbourhood had a sufficient number of new developments (two or more new apartment buildings) either in the centre or in the outskirt of the neighbourhood, 3) The neighbourhood had a sufficient number of buildings owned by housing companies (at least half of the buildings in the neighbourhood), 4) Infill development had taken place between 2000 and 2009. The reference neighbourhoods (control group) were selected by using the following three criteria: 1) the reference neighbourhood should be located in the vicinity of the case neighbourhood, 2) the reference neighbourhood should be similar to the case neighbourhood regarding the type of housing stock, accessibility and level of service availability, and 3) no infill development had taken place in the reference neighbourhood during the last decade.

Forming of the variables was performed as follows: first, a group variable was formed, naming the case neighbourhoods as 'treatment group' and reference neighbourhoods as 'control group', and a dummy variable was created for the time before infill development and the time after. After this, a group of structural variables were introduced to the model, describing the physical characteristics of the buildings, along with three environmental variables: distance to city centre, distance to seacoast and distance to green areas. The used variables are described in Table 2. The estimated regression equation took the following form: $P = \alpha + \beta_1(\text{CONDITION}) + \beta_2(\text{ELEVATOR}) + \beta_3(\text{ROOMS}) + \beta_4(\text{FLOOR}) + \beta_5(\text{SEA}) + \beta_6(\text{CBD}) + \beta_7(\text{GREEN}) + \beta_8(\text{TREAT}) + \beta_9(\text{AFTER}) + \beta_{10}(\text{TREAT*AFTER}) + \varepsilon$ where the dependent variable P is sales price (1000€) per m².

Table 2. Definitions of the used independent variables. Adapted from: Appendix D, Publication IV, Table 2, p. 162.

Variable	Description
CONDITION	Condition of the dwelling (0 = bad, 1 = average, 3 = good)
ELEVATOR	Dummy for the elevator (0 = no, 1 = yes)
ROOMS	Number of rooms, excl. kitchen
FLOOR	Floor number/ number of total floors
SEA	Distance to the seacoast (m)
CBD	Distance to the city centre (railway station) (m)
GREEN	Distance to parks or green areas (m)
TREAT	Dummy for the treatment group (0 = control group, 1 = treatment group)
AFTER	Dummy for the "after infill development" cases (0 = before, 1 = after)

Transactions up to five years before and after infill development were used as data, to ensure that expectations on prices based on future development would not yet have affected the prices and also to ensure that potential impacts of infill development could already be observed. The sale prices were adjusted for inflation using the Consumer Price Index, and setting 2012 as the base year.

2.2.3 Semi-structured interviews

The aim of Publication V was to attain a deeper understanding on motivation behind environmentally sustainable choices of households. This was done by conducting semi-structured interviews with Finnish solar PV system adopters, who were owners of single-family houses. While the focus of Publications III and IV was placed on apartment buildings, Publication V dealt with single-family houses. Although the majority of people living in urban areas typically reside in apartment buildings, the share of apartments located in single-family houses varies from 7% in Helsinki to above 30% in Oulu (Statistics Finland, 2019). Implementing a decentralised renewable energy system has been identified as an efficient means of detached houses to reduce their carbon footprint (e.g. Vezzoli et al., 2018). This is also a measure which often is decided upon independently by the household.

The semi-structured interviews were carried out by following a formal list of pre-generated questions, but the interviewer may have added or skipped questions depending on the course of the interview. Also, free discussion was encouraged. The responds of the interviewees and discussion was written down in details during the interview. 28 interviews were conducted in total, 6 of which took place face-to-face, and 22 via phone. A large geographical area was covered as the interviewees lived in different parts of Finland, although south-eastern areas of the country were overrepresented.

The qualitative data was processed and analysed by conducting thematic analysis, in which data is examined to identify common themes or patterns that come up repeatedly, as explained for example by Guest et al. (2012). Thematic analysis is a commonly used method of analysing qualitative data, particularly useful when the aim is to understand people's views, opinions and experiences from a data set, such as interview transcripts. As Braun and Clarke (2006) argue, thematic analysis is a flexible method which can be used in numerous ways. In this study the prevalence of a theme was counted in terms of number of interviewees mentioning a specific theme (not in terms of number of times the theme was brought up within the entire data set). Before conducting the interviews, an in-depth literature review was carried out regarding drivers and barriers for households adopting micro-generation technologies, based on which the framework for the study could be formed and the list of appropriate questions could be generated. By forming the theoretical framework beforehand, a 'deductive approach' was used to identify the themes (instead of an 'inductive approach' in which the identified themes are strongly linked to the studied data itself, and pre-existing coding is not used) (Braun and Clarke, 2006). Using this approach is reasoned because the aim of the study was to code the data to answer specific, preformulated research questions, instead of providing a possibility for the research questions to evolve during the analysis (as may happen in inductive approach). The research questions dealt with three question categories and two themes: 1. barriers to adopt PV systems (related to *adoption*), 2. experienced usability problems (related to *daily use*) and 3. pleasure provided to the adopters (related to *daily use*). The results were compared to the findings from the literature review, and for example the different barriers which had been identified and overcome by the respondets, could be grouped based on barrier categories identified in earlier research.

3. Summary of publications

This section summarises Publications I – V and their key findings, in regard of the research questions (RQ). All the five publications examined the topic of sustainable transformation of cities from different angles, the first two focusing on the city level and the three following publications on concrete actions of the household level.

3.1 Publication I: What are the differences between smart and sustainable cities?

Publication I aimed to answer RQ1: 'How do cities advance environmental sustainability by their target setting?'. By analysing a set of smart city and urban sustainability performance assessment frameworks and their numerous indicators, the aim was to study the similarities and differences of the 'smart city' and 'sustainable city' targets. The study was carried out by categorising the indicators under the three dimensions of sustainability (environmental, economic and social) and 10 selected sector categories. The results indicate a large gap between the two types of frameworks, particularly regarding the environmental sustainability dimension, which represented a clear minority in the smart city frameworks. This is illustrated in Figure 5, which shows the division of the aggregate number of indicators – of both smart city and sustainable city frameworks – addressing the three sustainability dimensions. The social sustainability dimension was addressed in both frameworks to a similar extent whereas economic sustainability was much more highlighted in smart city frameworks than in sustainable city frameworks. The results also indicate a clear difference in how much smart city and sustainable city frameworks emphasise various sectors: all the sectors that can be viewed as important regarding environmental sustainability – such as 'energy', 'transportation', 'waste and water management' and 'built environment' – were far less emphasised in the smart city frameworks than in the sustainable city frameworks. This uneven distribution of indicators addressing various sectors is illustrated in Figure 6: while sustainability frameworks strongly emphasise sectors such as 'natural and built environment', 'water and waste managent' and 'transport', these sectors are far less stressed in the smart city frameworks, which. Instead, the smart city frameworks strongly address sectors such as 'economy', 'education, culture, science and innovation' and 'well-being, health and safety'.

The main conclusion of the publication is that although environmental sustainability, attained with help of modern technologies, is a central target of smart cities, environmental sustainability aspects are however taken into account to a rather small extent in smart city frameworks. The results of the study hence suggest that following the targets of a 'smart city' does not automatically lead to advanced environmental sustainability. In order to ensure that sustainability aspects are not neglected when aiming for smart city targets, the publication suggests that a more accurate term 'smart sustainable cities' should be adopted.

While the aim of Publication I was to examine the differences between 'smart cities' and 'sustainable cities' at a conceptual level (by studying indicator frameworks) – and the results showed a significant gap between the targets – motivation was provided to further study the concpets on a practical level, which was the focus of Publication II.

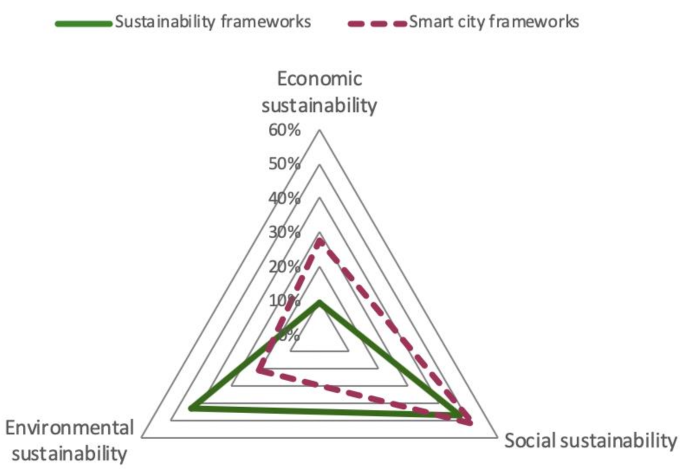

Figure 5. Economic, environmental and social sustainability dimensions addressed in the studied sustainability and smart city frameworks. Original figure: Appendix A, Publication I, Figure 2, p. 241.

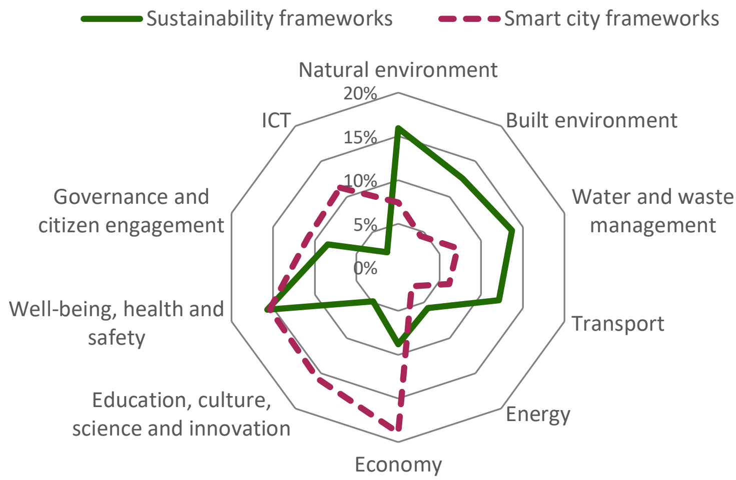

Figure 6. Various sectors addressed in the studied sustainability and smart city frameworks. Original figure: Appendix A, Publication I, Figure 4, p. 242.

3.2 Publication II: How do cities promote smart and sustainable goals? An evaluation of the city strategies of six largest Finnish cities

Similar to Publication I, Publication II also aimed to answer RQ1 'How do cities advance environmental sustainability by their target setting?' This study took a more practical approach by evaluating the contents of city strategies of six largest Finnish cities. The aim of the study was twofold: first, the city strategies were examined in order to determine how much the three dimensions of sustainability (social, economic and environmental) as well as various 'smartness aspects' were addressed in their strategies. Second, the study aimed to assess the extent to which smartness targets overlapped with sustainability targets. The study approach was similar to Publication I: by following the principles of content analysis, targets of the city strategies were unitised and distributed under 12 sector categories, 4 smartness categories and 3 dimensions of sustainability.

Although it was not presumed that all sectors, smartness aspects and sustainability dimensions would be addressed to a similar extent in the city strategies, the uneven distribution however provides interesting observations: first, both social and economic dimensions of sustainability were strongly highlighted in the city strategies, whereas environmental goals were far less addressed. This uneven distribution of goals under the three dimensions of sustainability is illustrated in Figure 7. Although the studied cities had also published their separate environmental action plans, the small number of goals related to environmental targets in the strategies is however a prominent fininding – considering the highly ambitious carbon-neutrality targets that the studied cities have declared. Second, a large number of goals were related to sectors such as 'economy & finance', 'governance' and 'population & social conditions' whereas 'energy' related goals were only rarely mentioned in the city strategies.

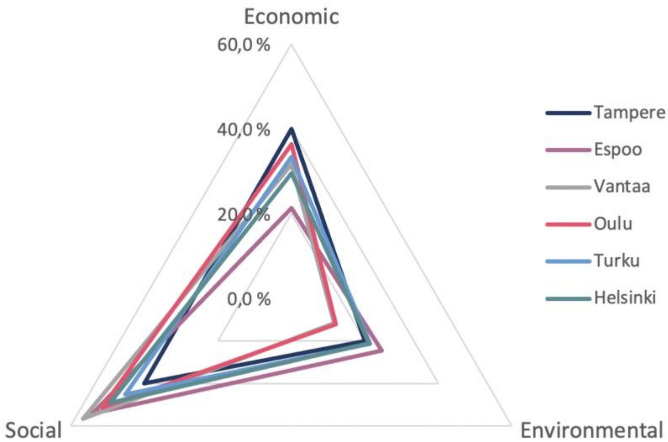

Figure 7. Emphasis on the three sustainability dimensions in the city strategies. Original figure: Appendix B, Publication II, Figure 4.

Regarding smartness targets, the study noted that they were not widely addressed in the city strategies although all the studied cities have declared their smartness goals and participate in smart city networks. When studying the overlapping of smartness goals and sustainability goals, the following observation was clear: while most of the smartness goals were related to social or economic dimensions of sustainability, only few were related to the environmental sustainability dimension. This is in line with the results elicited from Publication I, and likewise also Publication II suggests that the gap between the 'smart city' and 'sustainable city' targets might be remarkable.

Table 3 presents the aggregate number of goals presented in the city strategies addressing sustainability and smartness aspects, and the sectors that these goals are related to. The latter part of the table shows the number of goals addressing both a sustainability dimension and a smartness aspect, showing the extent to which these goals are overlapping. It is interesting to note that mainly goals which are related to economic and to some extent those related to social dimensions of sustainability, are also related to a smartness aspect. This suggests that, while the initial target of smart cities was to advance environmental sustainability by help of advanced technologies, this target has not been actualised on the strategic target setting level of cities.

Table 3. Goals addressing both sustainability dimensions and smartness aspects. Adapted from: Appendix B, Publication II, Table 3.

Sectors	Economy & Finance	Education	Energy	Environment & climate change	Governance	Health & safety	Housing & real estate	Population & social conditions	Sport, culture & recreation	Telecommunication & ICT	Transportation	Urban planning & construction
Sustainability dimensions in total												
Economic	**74**	13	0	2	19	3	4	6	3	3	5	13
Environmental	5	0	6	22	4	0	4	1	0	4	23	19
Social	27	31	0	2	**45**	16	15	**54**	16	2	4	13
Smartness aspects in total												
ICT & Technology	4	2	4	1	13	0	0	0	0	**22**	7	3
Human & social capital development	5	**16**	0	0	2	0	0	0	1	2	0	0
Entrepreneurship promotion & innovations	**20**	5	1	1	10	0	0	1	0	6	4	3
Cooperative approach & citizen engagement	6	3	0	0	**18**	0	1	6	1	2	1	5
Internationality & economic growth	**16**	0	0	0	0	0	0	0	4	0	1	2
Goals addressing both ECONOMIC SUSTAINABILITY and smartness aspects												
ICT & Technology	1	0	0	0	3	0	0	0	0	3	0	0
Human & social capital development	4	6	0	0	0	0	0	0	0	0	0	0
Entrepreneurship promotion & innovations	15	4	0	0	3	0	0	0	0	1	0	0
Cooperative approach & citizen engagement	1	1	0	0	1	0	0	0	0	0	0	0
Internationality & economic growth	12	0	0	0	0	0	0	0	2	0	1	1
Goals addressing both SOCIAL SUSTAINABILITY and smartness aspects												
ICT & Technology	0	1	0	0	1	0	0	0	0	2	0	0
Human & social capital development	5	14	0	0	3	0	0	1	1	1	0	0
Entrepreneurship promotion & innovations	3	4	0	0	3	0	0	1	0	0	0	0
Cooperative approach & citizen engagement	0	0	0	0	10	0	0	6	1	0	0	4
Internationality & economic growth	0	0	0	0	0	0	0	0	0	0	0	0
Goals addressing both ENVIRONMENTAL SUSTAINABILITY and smartness aspects												
ICT & Technology	1	0	3	1	0	0	0	0	0	4	5	1
Human & social capital development	0	0	0	0	0	0	0	0	0	0	0	0
Entrepreneurship promotion & innovations	3	0	0	1	1	0	0	0	0	3	2	1
Cooperative approach & citizen engagement	1	0	0	0	0	0	0	0	0	1	0	1
Internationality & economic growth	0	0	0	0	0	0	0	0	0	0	0	0

The findings of Publication II are in line with those of Publication I. Aiming for smartness targets may not automatically lead to improved environmental performance. In the city strategies these two types of targets overlap only rarely, although they both have a significant role in overall city targets. A remarkable finding is also the large gap between the ambitious carbon-neutrality targets and the low level of environmental aspects addressed in the city strategies. This suggests that there is a strong need for cities to elaborate their environmental targets, and strategic efforsta are required to integrate the targets within all major functions of the cities.

3.3 Publication III: Households' potential to decrease their environmental impacts: A cost-efficiency analysis of carbon saving measures

The following three publications take the study to the household level, exploring households' carbon mitigation actions from a practical angle by studying the impact of actions as well as motivational aspects behind the choices.

The aim of Publication III was to study the effects of households' everyday choices regarding carbon emissions and cost impacts. This publication answered RQ 2 'How can households decrease their environmental impacts efficiently?' but also RQ3 'In which ways can households benefit from implementing sustainable actions?', from an economic perspective. The actions selected for the study are typically presented as efficient measures for households to decrease their environmental impacts.

Figure 8 summarises the results of the study by showing both carbon and cost savings of the studied measures (each dot represents the results from one studied measure). As can be observed from the figure, the results of the study suggest that transport related choices, such as walking or cycling or using public transport instead of driving a car, may decrease carbon footprint much more efficiently than measures related to household electricity (such as turning of lights or using more energy efficient equipment). Various electricity saving measures of households provide significant outcome only if they are applied widely. Also replacing beef in one's diet with chicken or fish may provide an efficient way to decrease carbon footprint of households.

As is illustrated in Figure 8, individual electricity related actions do not provide remarkable cost savings, whereas some of the food related actions are both eco-efficient as well as cost-efficient. The results also indicate, that although transportation provides efficient means to reduce carbon footprint of households, all environmentally efficient transport choices might not always be very cost-efficient (see Figure 9). While using only bicycle and bus are shown as both carbon and cost-efficient means, replacing only some of the car travels with bus travels might end up in increasing costs. Choosing bus instead of car provides significant cost savings only if the passenger already has a monthly public transport travel card, which was not presumed in those scenarios in which only some of the car travels were replaced by bus travels. Detailed results from the carbon and cost analyses of all studied actions are presented in appendix C.

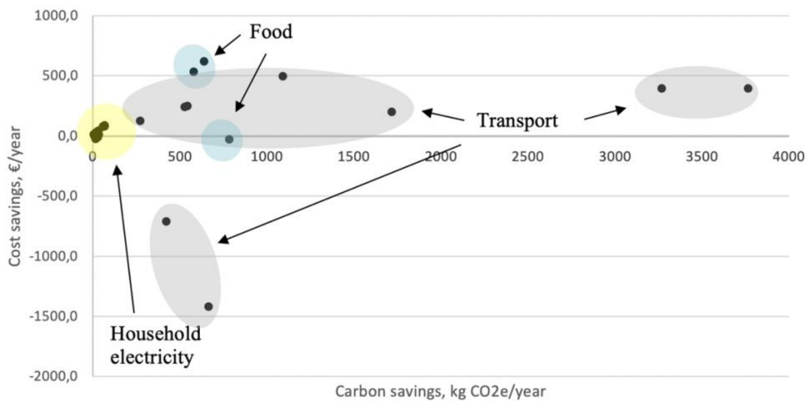

Figure 8. Cost and carbon savings from studied household choices. Each dot presents the results from one studied measure. Transport related choices are marked with grey background, food related choices with blue and household energy related choices with yellow. Original figure: Appendix C, Publication III, Figure 3, p. 205.

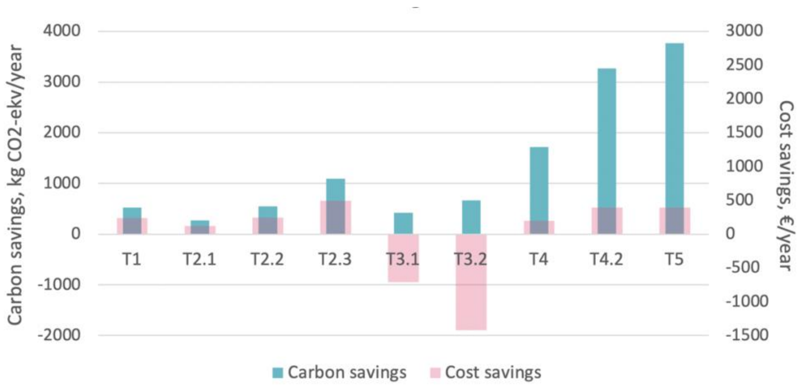

Figure 9. Co_2-eqv. and cost savings from different transport mode choices. T1=baseline scenario, T2.1-T2.3=using bicycle instead of car, T3.1-T4.2=using bus instead of car (to various extents), T5=using only bicycle and bus. Original figure: Appendix C, Publication III, Figure 2, p. 204.

Publication III suggests that all actions which are generally considered as eco-friendly, might however not lead to significant improvements of environmental performance. Therefore, better information is needed to support household decision making. Smart technologies could have an important role in this regard, and for example smart monitoring systems could provide case-specific on-time information, supporting households in making efficient choices. Addressing RQ3 'In which ways can households benefit from implementing sustainable actions?' Publication III focuses purely on economic benefits for households, the results suggesting that not all actions which improve environmental performance provide significant cost savings for households (which is often suggested to be a major driver for household's sustainable choices). The economic benefits are futher studied in Publication IV, also from a neighbourhood perspective.

3.4 Publication IV: Impact of infill development on prices of existing apartments in Finnish urban neighbourhoods

Similar to Publication III, also Publication IV responded to RQ 3 'In which ways can households benefit from implementing sustainable actions?' Also this study focused on understanding the economic benefits of environmentally friendly actions of households, but while Publication III dealt with independent choices of households, Publication IV took the study to the housing company and partly also neighbourhood level. The focus was placed on infill development, which is recognised as an efficient way to decrease carbon footprint of cities (e.g. Glaeser and Kahn, 2010; OECD, 2012; Bibri et al., 2020), dense urban construction typically being listed as a target in both sustainable and smart city frameworks. Regarding the study, it is important to understand, that in the Finnish system the decision making of housing companies - also the decision to sell building permit for infill construction - is dependent on collective decision of the individual shareholders (typically households), as explained by Falkenbach and Nuuja (2007).

The impact of infill development was examined by studying housing sale prices of seven case neighbourhoods with infill development and their respective reference neighbourhoods with no infill development. The results of the study indicate no significant differences in prices before and after infill development, thus it can be assumed that infill development does not increase the prices of existing housing, neither does it have a negative effect. Table 4 shows the results of the hedonic regression analysis of the sale prices in the seven studied neighbourhoods. TREAT*AFTER variable shows the effect of being located in both treatment group (neighbourhood with infill development) and "after" group (after infill development). However, the effect remains insignificant in most cases. The variable shows a more significant impact (marked as **) only in case 5, in which the price impact is opposite than assumed. This is probably due to the fact that the neighbourhood is located on an island, where closeness of the sea is a major attraction and an important factor regarding the prices. Figure 10 provides another type of illustration of the price development before and after infill development in one of the cases. While the prices of new apartments increase substantially, the price development of old apartments in the area, as well as in the reference neighbourhood, seem to follow similar paths. As economic gains for households – regarding increasing value of surrounding properties - are not substantial, they may not provide motivation for a housing company to sell building permit for infill development.

Table 4. Results of the hedonic regression analysis of the housing prices of seven case neighbourhoods. Original table: Appendix D, Publication IV, Table 4, p. 163. CONDITION = condition of the apartment on the scale of 0-3, ELEVATOR = whether the building has an elevator (yes or no), ROOMS = number of rooms, FLOOR = floor number, SEA= distance to the sea cost, CBD = distance to the city centre, GREEN = distance to the parks or green area, TREAT = whether the apartment is located in the "treatmet group" (meaging infill development takes place in the neighbourhood), AFTER= after "treatment" (infill development), TREAT*AFTER = the apartment is located in both TREAT and AFTER groups. The dependent variable is price (thousand €) per m2. The significance levels are ***<0.001, **<0.01, *<0.05. The standard errors of coefficients are reported in brackets.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
CONDITION	0.0991*** (0.0149)	0.120*** (0.0181)	0.0750** (0.0236)	0.050** (0.0187)	0.1360*** (0.0187)	0.0541** (0.0180)	0.0758*** (0.0011)
ELEVATOR	0.0695 (0.0401)	0.0079 (0.0422)	0.1287 (0.1104)	0.0161 (0.0446)	-0.1336** (0.0492)	-0.0249 (0.0436)	0.0253 (0.0256)
ROOMS	-0.2708*** 0.0161	-0.2565*** (0.0189)	-0.2929*** (0.0250)	-0.2427* (0.0216)	-0.091*** (0.0019)	-0.2384*** (0.0187)	-0.2798*** (0.0157)
FLOOR	-0.0617 (0.05654)	0.1484* (0.0633)	0.0852 (0.0709)	0.0438 (0.0657)	0.2984*** (0.0074)	-0.0107 (0.0675)	0.1189** (0.0399)
SEA	-0.00031 (0.00075)	- 0.00070*** (0.00019)	0.0017** (0.005519	-0.00019 (0.00021)	- 0.00076*** (0.00019)	-0.0003** (-0.00010)	4.677e-5 (8.573e-5)
CBD	0.00051 (0.00069)	0.000132* (0.000629)	-0.0016** (0.0005349)	0.00023 (0.0002)	0.00017** (6.175e-5)	0.00010 (9.64e-5)	-0.0002** (7.082e-5)
GREEN	0.00049*** (0.00012)	- 0.000495** (0.000185)	1.089e-6 (0.6365e-3)	0.00004 (0.00016)	-0.00018 (0.00023)	7.77e-5 (0.0001)	-5.349e-5 (0.00015)
TREAT	0.2943** (0.1074)	0.1873 (0.1094)	0.7863* (0.3022)	-0.0244 (0.1102)	0.2010* (0.100)	-0.7073** (0.2201)	0.4244* (0.1981)
AFTER	0.5759*** 0.0508	0.756*** (0.0751)	0.4324*** (0.0757)	0.8114*** (0.0504)	1.847*** (0.0574)	0.8183*** (0.1171)	0.8264*** (0.0321)
TREAT* AFTER	-0.0953 (0.0692)	-0.0298 (0.0905)	0.0641 (0.0852)	-0.1545 (0.0857)	-0.2703** (0.1018)	0.1426 (0.1310)	-0.1597* (0.0770)
Multiple R^2	0.6885	0.6012	0.7302	0.7499	0.7855	0.664	0.8112

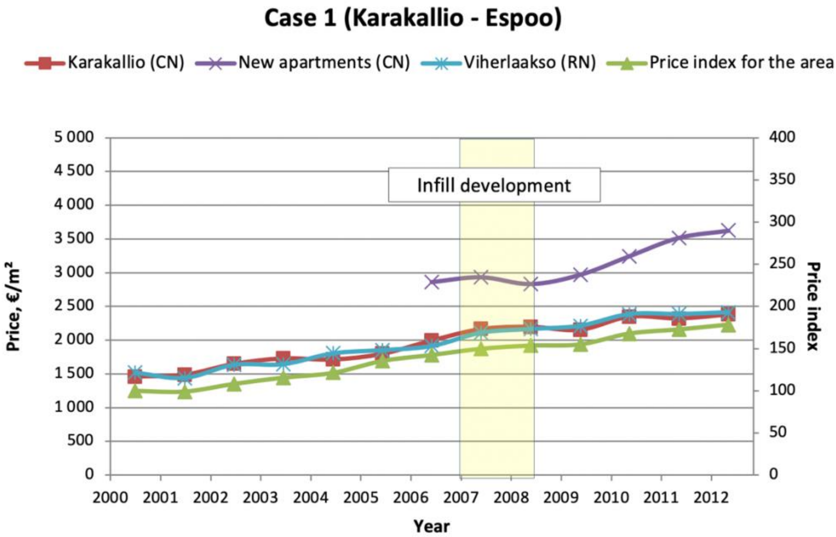

Figure 10. Mean values of sale prices before and after infill development in the case neighbourhood no. 1. Original figure: Appendix D, Publication IV, Figure 1, p. 163.

Although no significant value increase for existing apartments was observed, the publication however suggest that also positive benefits of infill development should be emphasized, such as improved local services, transportation options and infrastructure. The study points out that the direct economic revenue from selling building permit can be used to cover renovation costs of the building. This is actually a remarkable benefit, as infill development has been recognized as an important means to finance energy refurbishment of buildings (Kuronen et al., 2011) and also district scale refurbishment (Häkkinen et al, 2019). Also, although no upward motion of prices of surrounding housing of infill development was observed, neither was there a negative price effect. This suggests that other positive impacts could be used to silence the opposers of infill development and provide motivation for housing companies to sell land for this purpose.

Overall, both Publication III and IV respond to RQ3 ‘In which ways can households benefit from implementing sustainable actions?’ from the economic angle, focusing on a set of carbon mitigating actions. However, both studies suggest only modest economic benefits for households when adopting sustainable actions, indicating that also other type of benefits and motivation need to be provided. Hence, deep motivational drivers to implement environmentally-friendly actions are further studied in Publication V.

3.5 Publication V: Pleasure is the profit - The adoption of solar PV systems by households in Finland

Also Publication V answered RQ3 'In which ways can households benefit from implementing sustainable actions?', but instead of focusing on the economic benefits (as in Publications III and IV), this publication aimed to increase understanding on the deeper reasons and motives behind household choices. By conducting semi-structured interviews with 28 Finnish PV system adopters, the experiences of these forerunner households and their measures to overcome typical barriers were studied. The need for deeper understanding of the motives of household choices is supported for example by Creutzig et al. (2018) who present that as the focus of climate change mitigation is heavily put on the technology solutions of the supply-side, there is a strong need to understand the demand-side as well.

Overall, the interviewed households were very satisfied with their PV systems. The types of pleasure that households gained from impelementing the system can be divided into three categories: socio-pleasure, psycho-pleasure and ideo-pleasure, following the four pleasure-type framework introduced by Tiger (1992) (the fourth type is physio-pleasure but this was not experienced by the respondents). The results indicate that households adopting a PV system find great pleasure from the ability to produce clean energy effortlessly and providing information to others. Table 5 lists down the types of pleasures experienced by the interviewees and shows how they were categorized in the study. As is shown in the table, the respondents highlighted particularly factors which can be classified as psycho-pleasure and ideo-pleasure. Good user interface of the PV system, self-sufficiency of the household and sense of achievement create psycho-pleasure. Capability to produce clean energy and reduce emissions as well as provide information to others can be classified as ideo-pleasure. In addition, cooperation with other solar energy producers create a feeling of belonging to a social group (socio-pleasure). Instead, economic benefits from adopting a PV system remain low according to the interviewees but this was not considered very important. Although it was not brought up by the interviewees, assumably also some brand value may be provided by adopting a PV system, which could affect the sale price of the property.

The publication provides a fresh angle to the discussion on how to motivate households to make sustainable choices: as the experiences of the interviewed households indicate, economic benefits of adopting a PV system are not necessarily substantial (at least with a short time span and not at the time when the interviews were carried out – the prices of PV systems are however decreasing and in the future the situation might be different) Instead, other type of pleasure may be provided for the adopters. Regarding this dissertation, this is an important finding, because as mentioned in the introductory section, motivating households to take up sustainable actions is an essential topic regarding sustainable transformation of cities.

Table 5. Classification of pleasures experienced by PV adopters. Adapted from original table: Appendix E, Publication V, Table 3, p. 50.

Interviewee	Description of the most important pleasure	Type of pleasure		
		Socio	Psycho	Ideo
P1	Direct results of own experiments and constructions seen in practice. Savings gained.		x	
P2	Savings gained. A hobby.		x	
P3	It is fun to demonstrate the system to guests.	x		x
P4	Managing own production and consumption. 'I always have a good feeling when the sun is shining', 'It's nice to do something concrete to support something good' (referring to clean energy production).		x	x
P5	Own production of energy. The ability to advice other people in this area. Many new fiends and new contacts.	x	x	x
P6	'Double good feeling during the summer when the sun is shining' (referring to savings and pollution-free energy).		x	x
P7	Smaller electricity bill and lower CO_2 emissions.		x	x
P8	Lower cost of living.		x	
P9	Self-sufficiency, own energy production. Less dependency on energy companies.		x	
P10	'A shining sun is a pleasure to see' (referring to pollution-free energy').		x	x
P11	Energy self-sufficiency. Capability to produce aa renewable, new kind of energy for own use.		x	x
P12	Self-Sufficiency. Pollution-free energy.		x	x
P13	'Able to pioneer and offer information to others: come and see' (welcome to visit his plant).	x	x	x
P14	Environmental aspects. Great satisfaction from being able to do something and being a good example to others.	x	x	x
P15	Ease of operation. No work required to produce energy (opposite to burning fuels). Capability to produce energy imperceptibly, effortlessly and cleanly.		x	x
P16	Pollution-free (and free) energy.		x	x
P17	The results of own constructions seen in use. Keen to follow developments in this (his own) professional field after retirement. Feels that his reputation among his friends is positively affected by decreasing emissions.	x	x	
P18	Reduced carbon footprint.			x
P19	Capability to produce energy for own use effortlessly.		x	
P20	Capability to produce clean energy for own use.			x
P21	Ability to use renewable energy. Concrete benefit from reducing CO_2 emisssions.			x
P22	Savings gained. Environmental frindlines.		x	x
P23	Self-sufficiency. Effortlessness.		x	
P24	Effortlessness, no manual operation needed. Nice to follow the energy production.		x	
P25	Ease of use, carefree operation. Everything works automatically.		x	
P26	It is nice when the sun is shining and the system is working fine and savings are gained.		x	
P27	The possibility to fight against increasing energy costs.		x	
P28	Absolutely easy to use. A lot of energy produced during the summer: possibility to use any device in the household with self-produced electricity.		x	

4. Discussion

This section discusses the results of each individual publication in the light of the three research questions, but also in regard of the scope of the overall study – advancing carbon-neutrality targets of cities, from both city and household perspectives. Also, intersections of smartness and sustainability are discussed because of the pervasiveness of the 'smartness' in the 21st century city development. Although the five individul studies focus on both city and household levels, it is however importante to recognize that cities and households should not be seen only as separate actors. The strategies and central actions of cities are based on political decision making – by decision makers selected by the citizens. Likewise, households do not operate in isolation as their choices (especially those related to housing) may strongly be influenced by cities.

The results of Publications I and II indicate a remarkable gap between the targets of 'sustainable cities' and 'smart cities'. Seemingly, smartness targets are very much related to economic and social aspects, although the original objective of smart cities was to cut greenhouse gas emissions (e.g. Wang and Moriarty, 2019; Yigitcanlar and Kamruzzaman, 2018). This indicates that when cities strive for their carbon-neutrality targets, it should not be assumed that 'smartness' provide an all-encompassing solution, as its targets are very different. This notion is supported for example by Vanolo (2015) and Shelton et al. (2015) claiming that the concept of smart city has been adopted only for branding or marketing purposes, while the integrated approach covering sustainability concerns is lacking. However, another potential view is that although the targets of sustainable and smart cities are different, cities can utilise some of the 'smart measures' and smart technologies in the pursuit of carbon neutrality targets. At the city scale, for example smart grids – enabling demand response and hence utilising of decentralized renewable technologies – have been proven as efficient in decreasing carbon emissions (e.g. Elkhorchan and Grayaa, 2016). It has also been suggeted that smart mobility, with the combination of "shared, electric, and automated mobility" may have an important role in the reductions of greenhouse gas emission of mobility

(Manders et al., 2020). It should however be noted that when applying new technologies, also the environmental impacts of these technologies should be assessed in order to understand the overall effects. This approach has been recognised by the International Telecommunication Union (ITU), suggesting that environmental impact calculations should also assess whether producing of the smart equipment, used to cut carbon, has higher environmental impact than the the equipment can mitigate during its lifetime (ITU, 2015).

Moreover, the findings of Publication II – showing that environmental sustainability goals are not extensively expressed in the city strategies – is interesting in the light of the highly ambitious carbon-neutrality targets, which all the studied cities have declared. Reaching such an ambitious goal would require integrating the targets within all sectors and functions of the city system – instead of presenting the measures only in a separate climate action plan. Also, 'smartness targets' were not extensively expressed in the strategies, although all the studied cities are participating in smart city networks. This is however not a remarkable deficiency, because smartness should be seen merely as a tool for reaching environmental sustainability instead of a target in itself. Based on the results of Publication II it can be suggested that when cities create their strategies, they need to incorporate carbon-neutrality targets to a much larger extent and across all sectors. Strategies also need to clearly point out the links between smartness and environmental sustainability. Otherwise, there is a risk that carbon reduction targets and smartness targets will remain as two separate sets of goals, merely presented in their own action plans, and hence practical applications of smart actions will not advance sustainability targets.

Regarding household level, the results of Publication III show that not all household actions, which are generally considered as low-carbon measures, may substantially decrease GHG emissions. It is crucial to provide more case-specific information for households, and smart technologies could have a key role here. As has been suggested also by Gölz and Hahnel (2016) and Pasini et al. (2017), smart feedback systems or personalized information could motivate to change energy behavior. For example, Ueno et al. (2006) report 9% energy savings for a household applying smart energy consumption information system. However, not all studies suggest such a positive outcome, and for example, Del Rio et al. (2020) warn that if IoT is poorly applied, it might actually lead to increased electricity consumption. It is important to note that the selected perspective of the environmental impact study was only the use stage, with a one-year time span, and thus a life-cycle approach was not considered. A holistic approach would consider also the construction and manufacturing stages, as well as end-of-life stages encompassing waste disposal. Ideally, consumers would be provided with information on all life-cycle stages when acquiring a commodity (be it a car, bicycle, house or food item), based on which they would be able to make their decision. However, currently consumers are mainly aware of the the use-stage impacts, and for example energy certificates of buildings do not give information on the construction-stage GHG emissions.

The results of publication III also provide a fruitful ground for the discussion about the roles and responsibilities of cities and households in the carbon mitigation endeavour. It is important to understand the extent to which households have the possibility to make sustainable choices. This topic has been studied by Kyrö et al. (2011), the results interestingly showing that residents of apartment buildings in Finland directly control only 11% of the total energy consumption of the household. It seems that while households are under great pressure to decrease their carbon emissions, a clear understanding on significance of various actions is however lacking. Households have largely varying possibilities to cut carbon emissions, depending on their geographical location as well as their housing mode. While applying smart technologies (as mentioned above) is up to the decision of households, cities do have an imporant role in creating a favourable environment for households to mitigate carbon footprint. Of the four areas of living studied in Publication III, the role of city is particularly strong regarding transportation. First, land use planning determines the locations of various functions of the city (residential areas, commercial areas, offices etc.) hence affecting travel distances. Second, households' efforts are highly dependent on the actions of the cities in providing extensive and affordable public transportation. Cities are also responsible for providing infrastructure for sustainable transportation modes such as cycling and walking, and they may directly or through regulations increase provision of charching stations for electronic vehicles. It should also be recognised that – partially due to the rise of smart technologies – new sustainable transport networks are emerging (called as Mobility as a Service, MaaS) in which the use of various transport modes is more flexible (e.g. Strömberg et al., 2018). Although MaaS unites all types of service providers (both public and private), the MaaS platform, integrating the services, may be provided by the city.

Results of publication IV suggest that infill development – having an important role in decreasing carbon footprint of cities – does not necessarily provide economic benefits for the surrounding neighbourhood. As was discussed in Section. 3.4., several other benefits are however provided for the surrounding neighbourhood, and these should be highlighted when promoting infill development. It is evident that cities have a significant role in advancing infill development, although property owners decide about selling building permit for this purpose. In Finland, municipalities have a statutory monopoly in steering land use (Behrend, 2017) and hence compact development is ultimately controlled by cities. Cities have the possibility to increase attractiveness of infill development also by other means such as setting appropriate fees and speeding up zoning processes.

Publications III, IV and V all study motiovational factors of sustainable choices, all publications suggesting that economic benefits of the studied carbon cutting actions may remain modest. While financial aspects have been presented as central motivational factor in household energy studies (e.g. Zou and Yang, 2014), the results of this dissertation show that mechanism behind economic advantages of various actions need to be understood better. Although the forerunner households interviewed in Publication V did not consider monetary benefits as important, financial support probably continues to be an important mechanism in motivating households to implement actions. While the financial support tools are often determined at a national level, cities do have a role in advancing household actions by providing affordable public transportation and setting appropriate fees regarding infill development (as mentioned above), to name but a few.

Publication V seeks to find deeper motivation behind implementing sustainable actions, and the types of pleasure discovered from the interviews with forerunner households provide a new viewpoint. The most important benefits experienced by the interviewees were the joy of being able to produce clean energy and to provide information to others. Although the interviewed households serve as *forerunners*, this result can however be seen as significant in speeding up the uptake of carbon cutting actions. According to the innovation diffusion theory by Rogers (2003), *opinion leaders* may “serve as an apt model for the innovation behaviour of the followers” suggesting that in the case of PV systems, content early adopters could lead the way in further adoption of the innovation.

Finally, taking the discussion back to the sustainable city vs. smart city question, another intersection may be provided (in addition to the utilisation of information technology for reaching of environmental sustainability). One commonly highlighted target of smart cities is the social capital development (e.g. Sodiq et al., 2019; Nam and Pardo, 2011), which according to Kuzior and Sobotka (2019) occurs when “*people have and forge good relations with other members of the* community*, when they trust one another and collectively undertake actions aimed at improving their living conditions*”. A large body of literature link high social capital to improved environmental performance and advanced sustainable development (e.g. Zhou et al., 2020; Kusakabe, 2010). Studies also show a positive effect of increased information on environmental behavior (e.g. Goldman et al., 2020) emphasizing the importance of “informed citizen”, which is a commonly highlighted target of smart cities (Sodiq et al., 2019). It can hence be suggested that smart city targets accompanied with increased social capital development and emphasis on information guidance, may have a positive impact on sustainable transformation of cities: ultimately this could change households' attitudes and increase their interest in carbon reduction, leading to more environmentally sustainable behaviour.

4.1 Contribution of the dissertation

While information on technical measures to reach carbon-neutrality targets of cities is vast, there is still lack of information about advancing the uptake of the measures and speeding up sustainable transformation. This dissertation increases understanding on this topic, on both city and household levels, however not ignoring the interconnectedness and interdependence of these levels. The novelty of this study hence is in deepening knowledge on issues, which are under constant academic debate. First, it participates in the ongoing discussion on the usefulness of smart city strategies in advancing environmental sustainability and carbon-neutrality targets of cities. Second, it provides new knowledge on sustainable actions adopted by households, both from carbon mitigation and motivational perspectives. Each individual publication provides its own specific contribution as prsented below.

Publication I studied the similarities and differences of the 'smart city' and 'sustainable city' concepts and their respective frameworks. At the time of publication, this study was among the first studies to present a comprehensive comparison analysis. Also, the concept of 'smart sustainable cities', earlier introduced by Kramers et al. (2014), had not yet been widely embraced, and hence Publication I served as a forerunner in suggesting the use of this concept instead of 'smart cities'.

Analysing the overlappings of the 'smart city' and 'sustainable city' goals on a more practical level was the topic of Publication II. Although during recent years the studies dealing with this topic (similarities and differences of smart and sustainable cities) have proliferated, Publication II however provides a unique angle by examining the city strategies and how both smartness and sustainability targets are expressed in them. An important finding of Publication II – the low presence of environmental sustainability aspects in the city strategies – is significant, for reasons described in the discussion section. The finding calls for a clear vision and more explicit description of measures by cities in order to reach the highly ambitious carbon-neutrality targets.

Carbon saving measures at the household level was studied in Publication III. Several studies have analysed the composition of households' greenhouse gas emissions but according to the authors' awareness, no other studies have examined extensively both GHG impacts as well as economic impacts of households' everyday choices. The findings of this publication are significant regarding the discussion on the role of households in mitigating climate change, and the extent to which households are able to make significant contribution to carbon reduction targets of cities.

Impact of infill development on housing prices of existing apartments in Finnish neighbourhoods was studied in Publication IV. New information was provided, since earlier studies on price impact of infill development have mainly focused on different geographical area such as US and Asian cities, or different housing type such as single-family houses. Also, revenues from selling building permit to new development provides housing companies a possibility to cover building refurbishment costs. While this has been recognized as a significant benefit, studying the potential value increase of existing apartments provides a fresh angle. The link to environmentally sustainable development of cities lies in the recognized carbon mitigation potential that compact development holds (Wang et al., 2018; Bibri et al., 2020). The benefits for surrounding neighbourhoods needs to be understood better, because in existing neighbourhoods it is often the housing companies who make the decision about selling land for infill construction – and they need to be motivated to do so.

With the ambitious carbon reduction targets, it is important to motivate households to take actions. However only little is known about deep motivation of households. Hence the novelty of Publication V is the information provided about early adopters' experiences, which may serve as useful in speeding up sustainable processes.

4.2 Limitations of the study

Categories created by the authors were used to assess differences and similarities of smartness and sustainability targets in both Publications I and II. Although the used categories were based on literature sources, another study might have used other type of categorization, resulting in different outcome. However, another categorization would not have altered the main findings of the studies, which suggested a large gap between sustainability and smartness targets. It should also be noted that the studied indicators were studied as presented in the frameworks, which does not mean they would necessarily provide the most accurate ways to measure the respective issues.

The environmental impacts considered in Publication III were limited down to carbon footprint. Other important sustainability indicators, which were disregarded in the study are water, waste and pollution, to name but a few. Hence it should be noticed that although cities currently focus strongly on carbon reduction, overall environmental sustainability consists of larger set of environmental targets. Another recognized limitation of Publication III is that rebound effect (see e.g. Bjelle et al., 2018) was not considered in the study. In case that the study would have tried to estimate the aggregate carbon saving potential of a household (instead of studying individual actions and their impacts), it would have been essential to include the rebound effect into the analysis.

Challenges regarding Publication IV were related to the data, as in some case neighbourhoods the number of transactions was rather small. However, the used database is the most comprehensive database for housing transactions in Finland and it is widely used in housing market studies. As was noted in Publication V, installation of a PV system requires a rather significant initial investment, which makes adopting this measure challenging for low-income households. Thus, it should be recogniced that the interviewed PV system adopters belong to upper-middle class and many of them have a high educational background, which might also reflect the responds.

While the focus of the overall dissertation was placed on the city and household levels, the role of industry, business actors, energy companies etc. were not included into the study. Companies may speed up sustainable transformation of the built environment in numerous ways, for example by setting requirements for the environmental impacts of their office or production facilities or by choosing locations which support the use of public transportation by employees. Understanding the sustainability actions by companies and business actors is however another field of research, which has been successfully explored. For example Chams and García-Blandon (2019) studied the relation between board directors and the sustainable performance of a company, and Saunila et al. (2019) studied the relation between smart technologies and sustainability of a company, to name but a few. Although this dissertation does not consider the role of other actors, the importance of them should however not be neglected when aiming for the sustainability targets of a city.

4.3 Future research needs

This dissertation takes a wide approach to the topic of sustainable transformation of cities, by focusing on both city and household levels. The first research aim was to assess the similarities and differences between the targets of ‘smart’ and ‘sustainable’ cities, suggesting a rather large gap between them. Although during recent years, several outstanding studies have been conducted assessing the impact of ‘smart measures’ in regard of carbon reduction targets (e.g. Wang et al., 2019; Ahad et al., 2020), more studies with a practical approach are still needed in order to determine which of the smartness aspects can serve as useful. One important topic that should be futher studied is the environmental impact caused by the use of smart technogolies. This has been recognized by ITU (International Telecommunication Union), as was discussed in the discussion section.

Regarding household actions, Publication III highlights the role of information in activating and motivating households to take up carbon reducing actions, and the suggestion is that smart technologies could be useful for this purpose. Studies on influence of smart meter technologies on energy behavior have suggested a rather significant impact (e.g. Ueno et al., 2006) but more information is needed on how smart technologies could be utilized regarding carbon reductions in all areas of living.

Finally, motivational drivers for households implementing carbon saving actions must be further studied to be able to speed up the transition. As was suggested by Publications III and IV, financial benefits might not always be provided by environmentally friendly actions and neither are they seen as essential by early adopters (Publication V). Following the theme of Publication V, it would be useful to continue to deepen knowledge on motivation of households adopting sustainable energy choices (called 'sociology of energy'). Qualitative approach with deep interviews serve as method for this purpose, although combined with studies on willingness to pay may provide fruitful information for cities and at the national level, where the decisions about financial support are made.

5. Conclusions

Cities around the world have actively committed to fighting climate change by declaring ambitious carbon-neutrality targets. Simultaneously cities are publishing smart city strategies, although a commonly accepted definition for smart cities is still lacking. Cities' possibilities to reach their carbon-neutrality targets are however limited if not all actors of the cities are integrated into the endeavor. As households are responsible for a great share of global greenhouse gas emissions, activating and motivating households to reduce their carbon footprint can be seen as the key in reaching cities' carbon-neutrality targets.

This dissertation increases understanding on the measures to advance sustainable transformation of cities by studying environmental sustainability efforts from the perspectives of cities and households. The first two publications approached the topic by analysing target setting of cities and studying how environmental sustainability targets are being expressed 1) in smart city frameworks and 2) in the city strategies. The following three publications dealt with the household level, Publication III aiming to increase kowledge on environmental impacts of household actions, and both Publications III and IV increasing knowledge on economic benefits of various household measures. Finally, publication V studied deeper motivational factors behind sustainable choices of households.

The following conclusions can be summarised based on the results of the five individual publications. First, in the pursuit to reach environmental sustainability targets and mitigate carbon emissions, cities need to adopt a clear approach. Aiming for smart city targets as such does not automatically lead to an environmentally sustainable outcome (Publications I and II). Instead of using the concept of 'smart cities', the studies encourage adopting the concept of 'smart sustainable cities' to ensure that all dimensions of sustainability (social, economic and environmental) are covered. While all large Finnish cities have declared their ambitious carbon-neutrality targets, interestingly these targets and respective measures are not widely presented in the city strategies (Publication II). Rather the focus of the strategies is placed on social and economic aspects (in this order), while environmental sustainability goals and measures are presented in more details in separate climate action plans. Thus, strategic efforts are needed to integrate the carbon reduction targets into all sectors and functions of the city.

Second, all efforts by households to adopt environmentally sustainable actions do not automatically lead to significant cuts in carbon footprint (Publication III). The case study of an average Finnish household showed that while carbon impact from electricity-related choices remained only modest, more significant impacts could be provided by choices related to transportation modes or food consumption. The role of information is crucial in this regard, ensuring that households are able to make choices which are truly influential. Smart technologies can play a key role here, and for example with help of smart metering and monitoring systems with on-line (and on-time) feedback, households could gain better understanding of both the current situation as well as impacts of efficient case-specific measures.

The third main finding is related to motivational factors of households' sustainable actions. The results show that benefits from carbon cutting actions are not always of economic nature (Publication III). Electricity-related measures of households may not provide remarkable cost savings to the same extent that some transportation-related choices might do. Economic benefits were also studied in Publication IV, placing the focus on infill development. The results indicate that infill development may not have significant positive price impact on the value of existing apartments. However, the surrounding neighbourhood might benefit from improved services, transport network and infrastructe, and the revenue that the housing company gains from selling land migh have an important role in financing building refurbishment. Finally, Publication V studied experienced benefits and motivational factors of households who had adopted carbon mitigating actions by installing a PV system. The interviewed households highlighted the experienced pleasure which was related to being able to produce clean energy (psycho-pleasure) and being able to provide information to others (ideo-pleasure). Experienced economic benefits remained modest, but the interviewed households did not consider this as a significant drawback.

To conclude, all actors should be seen as responsible when aiming for sustainable transformation of the cities. Households do have a substantial role in reducing carbon emissions but some of the measures available for them also require efforst from the city. When cities aim for ambitious carbon reduction targets, along with their smart city strategies, it is essential to clarify which of the smart measures are useful in regard of the environmental sustainability transition. For households' carbon mitigation actions, the role of information is crucial and smart technologies can surely play a key role here. In addition, although intersections of smart cities and carbon reduction goals are usually seen in the technological development, also smart city targets such as 'informed residents' and 'social capital development' may prove useful in regard of motivating citizens to make sustainable choices.

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