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Corporate and city GHG inventories

Impact on global CO₂ emissions
when considering electricity and CHP-based district heating

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Abstract

One initiative to reduce greenhouse gas (GHG) emissions involves developing standards for GHG inventories. Companies and cities (regions) can use GHG inventories to compile and report their GHG emissions. Standards for corporate and city GHG inventories often claim that GHG inventories can be used for identifying emissions opportunities, building reduction strategies and setting, measuring and reporting emissions targets. Attributional emissions factors are generally used in corporate and city GHG inventories. For purchased electricity, heat and steam, this means using average emission factors for regional or national production of each energy carrier. Also contractual emissions factors can be used. Changes in emissions from affected production elsewhere are not included. For purchased electricity and district heating (DH), a GHG inventory can be improved by lowered purchases or by purchasing a different energy carrier.

Furthermore, combined heat and power (CHP) technology can help reduce global GHG emissions in the supply and conversion of energy, as CHP production is more efficient than conventional separate production of electricity and heat. In CHP production, excess heat from electricity production is utilised for heating buildings, hot water, industry processes etc., either directly or through DH systems.

This thesis analyses how emissions reduction measures based on corporate or city GHG inventories, carried out using GHG Protocol standards, affect global CO₂ emissions when electricity or CHP-based DH is affected. The incentive of a GHG inventory to a company purchasing electricity and DH, and to a city regarding purchases and production of electricity and DH in its region, is analysed. This is done for GHG inventories conducted in a nation where electricity produced within the nation is regarded as CO₂-lean (Sweden) and in a nation where it is more CO₂-rich (Germany). The indirect incentive to the DH company to change its production, in order to improve the GHG inventory of its customers and of the city where the DH system is located, is also analysed. Consequential analyses are used to assess how global CO₂ emissions are affected by changes in purchases or production of electricity and DH that are incentivised by the GHG inventories studied. These consequential analyses include changes in emissions from affected electricity production elsewhere.

The results show that the strength of incentive to reduce purchase of electricity or CHP-based DH by a company or in a city can differ between GHG inventories and consequential analysis. This is most clear when electricity produced within the nation is regarded as CO₂-lean (Sweden) while affected electricity production elsewhere is CO₂-rich. For replacing purchases of CHP-based DH with electricity, or vice versa, the incentive in a GHG inventory can be the reverse of that in a consequential analysis. Moreover, the incentive to lower the use of electricity is lost when contractual emissions factors with zero emissions, such as

renewable electricity guarantees of origin (RE-GOs), are used. In addition, purchase of electricity RE-GOs, which have a large surplus and no requirement of additionality, is less likely to cause a corresponding increase in production of renewable electricity.

Furthermore, when the highest emission reduction per Euro invested is sought (e.g. when investment resources are limited), the investment ranking of a heat-only boiler and a CHP plant can differ depending on whether the focus is on improving a city GHG inventory or lowering global CO₂ emissions. Moreover, if the DH company improves (reduces) the average emissions factor for DH, it improves the GHG inventory of its customers and of the city where they are located. In a DH system based on bio-fuelled CHP production, the average emissions factor for DH improves when CHP electricity production is lowered to the extent that production of heat at the oil-fuelled heat-only boiler (used for peak heat production) is minimised. However, according to consequential analysis, this would lead to an increase in global CO₂ emissions.

Based on the results of this thesis, it is concluded that measures which include changes in purchases or production of electricity or CHP-based DH can increase global CO₂ emissions when based on how corporate or city GHG inventories in general value CO₂ emissions of electricity and DH. It is therefore unfortunate that GHG Protocol standards for corporate and city GHG inventories advocate basing emissions reduction decisions on GHG inventories. There is nonetheless an obvious risk of reported and communicated GHG inventories being used as a basis for emissions reductions decisions. If the aim is actual reduction of global CO₂ emissions, average or purchased emissions factors should not be used for purchased electricity and CHP-based DH when assessing, reporting or communicating the impact of companies and cities (regions) on CO₂ emissions. Instead, a consequential approach should be used for climate evaluation of purchased electricity and DH.

Sammanfattning

Ett av många initiativ för att minska utsläpp av klimatpåverkande gaser är framtagandet av regelverk för klimatredovisningar. Klimatredovisningarna kan användas av företag och städer (regioner) för att sammanställa och rapportera om företagets eller stadens utsläpp av klimatpåverkande gaser. I regelverken för framtagande av klimatredovisningarna betonas ofta att klimatredovisningen kan användas för att identifiera var utsläppsminskningar kan göras, att utveckla strategier för att minska klimatpåverkande utsläpp samt för att sätta, mäta och följa upp mål för klimatpåverkande utsläpp. En klimatredovisning innehåller vanligtvis bokföringsvärden, vilket innebär att lokala genomsnittliga utsläppsfaktorer används för köpt el och värme. Även köpta utsläppsfaktorer kan användas. Klimatredovisningen inkluderar inte ändringar i utsläpp från produktion som påverkas någon annanstans. En klimatredovisning kan förbättras t ex genom att mindre energi köps eller genom byte av energibärare.

För el- och värmeförsörjning kan kraftvärmeteknik bidra till minskade globala utsläpp av koldioxid (CO_2), eftersom kraftvärmeproduktion är mer effektivt än separat produktion av el och värme. Vid kraftvärmeproduktion tas överskottsvärmen från elproduktionen tillvara för att värma byggnader, varmvatten, industriprocesser mm, antingen direkt eller via fjärrvärmesystem.

I denna avhandling analyseras hur globala utsläpp av CO_2 påverkas av åtgärder som påverkar förbrukning eller produktion av el och fjärrvärme, när beslut om sådana åtgärder baseras på ett företags eller en stads klimatredovisning, gjorda enligt Greenhouse Gas Protocols regelverk. Incitamenten i ett el- och fjärrvärmeköpande företags klimatredovisning och i en stads klimatredovisning analyseras. Detta görs för klimatredovisningar utförda i ett land där elproduktionen inom landet är CO_2 -mager (Sverige) och ett land med mer CO_2 -rik elproduktion (Tyskland). Dessutom analyseras de indirekta incitament som dessa klimatredovisningar ger till det lokala fjärrvärmeföretaget att ändra sin produktion för att förbättra sina kunders klimatredovisningar och klimatredovisningen för staden där fjärrvärmeverksamheten finns. Konsekvensanalyser görs för att beräkna hur olika åtgärder som stöds av klimatredovisningarna påverkar globala CO_2 -utsläpp. I konsekvensanalyserna inkluderas också förändringar i utsläpp från påverkad elproduktion, även om den förändringen sker någon annan stans.

Resultaten visar att styrkan i incitamentet att minska ett företags eller en stads inköp av el eller fjärrvärme kan skilja sig mellan en klimatredovisning och en konsekvensanalys. Detta är särskilt tydligt när klimatredovisningen görs i ett land där elproduktionen inom landet är CO_2 -mager (Sverige) medan den påverkade elproduktionen är CO_2 -rik. När det gäller utbyte av fjärrvärme mot el eller tvärtom kan en klimatredovisning ge motsatta incitament jämfört med den ledningen en konsekvensanalys ger. När köpta emissionsfaktorer med nollutsläpp för el

används, t ex förnybara ursprungsgarantier, försvinner incitamentet att minska elanvändningen. Det är dessutom mindre sannolikt att ett köp av förnybara ursprungsgarantier för el medför motsvarande ökning av produktion av förnybar el, då överskottet av förnybara ursprungsgarantier för el är stort och additionalitetskrav saknas.

När investeringsresurser är begränsade kan det vara av intresse att utvärdera vilken investering som ger mest reduktion av klimatpåverkande gaser per investering. Avhandlingens resultat visar att investering i hetvattenproduktion och kraftvärmeproduktion då kan komma att sinsemellan rangordnas olika, beroende på om målet är att förbättra stadens klimatbokslut eller om målet är att minska globala utsläpp av CO₂.

Om fjärrvärmeföretaget förbättrar (minskar) genomsnittlig emissionsfaktor för sin fjärrvärme, förbättras klimatbokslutet för deras kunder och för staden där fjärrvärmesystemet är beläget. Resultaten visar också att i ett fjärrvärmesystem, som baseras på ett bioeldat kraftvärmeverk och där olja används för efterfrågetoppar när det är som allra kallast, förbättras fjärrvärmens emissionsfaktor när elproduktionen i kraftvärmeverket minskas. Dock visar konsekvensanalysen att ett sådant agerande kan medföra ökade globala utsläpp av CO₂.

Baserat på resultaten dras slutsatsen att beslut om åtgärder, som påverkar köp eller produktion av el eller kraftvärmebaserad fjärrvärme, kan orsaka ökning av globala CO₂-utsläpp om de baseras på de incitament ett klimatbokslut ger. Det är därför olyckligt att GHG Protocols regelverk för företags och städers klimatbokslut rekommenderar att klimatboksluten används för beslut som avser att minska utsläpp av CO₂. Även om de inte rekommenderade detta, finns ändå en uppenbar risk att rapporterade och kommunicerade klimatbokslut används som bas för beslut om åtgärder som syftar till minskade utsläpp av CO₂.

Om syftet är minskade globala CO₂-utsläpp bör genomsnittliga och köpta emissionsfaktorer inte användas för klimatvärdering av köpt el och kraftvärmebaserad fjärrvärme när ett företags eller en stads (regions) klimatpåverkan beräknas, rapporteras eller kommuniceras. För klimatvärdering av köpt el och fjärrvärme bör i stället en konsekvensbaserad metod användas.

List of appended papers

The thesis is based on the work described in the papers listed below, referred to in the text by their Roman numerals, and on additional analyses. Section 5.1.1 describes the parts of the work presented in this thesis covered by each paper and the parts appearing only in the thesis. The papers are appended at the end of the thesis.

- I. Difs, K., Bennstam, K., Trygg, L., Nordenstam, L., 2010.
Energy conservation measures in buildings heated by district heating - A local energy system perspective. Energy 35(8), pp. 3194-3203.
<https://doi.org/10.1016/j.energy.2010.04.001>
- II. Nordenstam, L., Bennstam, M., Ödlund (formerly Trygg), L., 2017.
Considering investment resources when assessing potential CO₂ reductions of CHP - a case study. Energy Procedia 116, pp. 172-284.
<https://doi.org/10.1016/j.egypro.2017.05.074>
- III. Nordenstam, L., Djuric Ilic, D., Ödlund (formerly Trygg), L., 2018.
Corporate greenhouse gas inventories, guarantees of origin and combined heat and power production - Analysis of impacts on total carbon dioxide emissions. Journal of Cleaner Production 186, 203-214.
<https://doi.org/10.1016/j.jclepro.2018.03.034>

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Abbreviations

A0-A2	Scenarios A0-A2
B0-B2	Scenarios B0-B2
BSM	Benefit-sharing method
C0 _{bio} - C5 _{bio}	Scenarios C0 _{bio} - C5 _{bio}
C0 _{gas} - C4 _{gas}	Scenarios C0 _{gas} - C4 _{gas}
C40	Cities climate leadership group
CHP	Combined heat and power
City Standard	The GHG Protocol ‘Accounting and Reporting Standard for Cities’
CO ₂	Carbon dioxide
CO _{2eq}	CO ₂ equivalent
Corporate Standard	The GHG Protocol ‘Corporate Accounting and Reporting Standard’
DH	District heating
EU	European Union
FGC	Flue gas condensation
GHG	Greenhouse gas
HOB	Heat-only boiler
ICLEI	International Council for Local Environmental Initiatives (now ICLEI-Local Governments for Sustainability)
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
MODEST	Model for Optimisation of Dynamic Energy Systems with Time-dependent components and boundary conditions
NGCC	Natural gas combined-cycle plant
NGO	Non-governmental organisation
NPV	Net present value
P:A1	Profile for changes in DH demand in scenario A1
P:A2	Profile for changes in DH demand in scenario A2
P:Cx	Profile for changes in DH demand in scenarios C0 _{bio} - C5 _{bio} and C0 _{gas} -C4 _{gas}

RE-GO	Renewable guarantee of origin
SCOP	Seasonal coefficient of performance
TvAB	Tekniska verken i Linköping AB (publ)
WBCSD	World Business Council for Sustainable Development
WRI	World Resources Institute

Nomenclature

$a_{e,i}$	Share allocated to electricity for fuel i
$a_{h,i}$	Share allocated to heat for fuel i
CF_t	Expected net cash flow caused by the investment in period t (€)
$EAAR$	Equivalent annual annuity ratio
$E_{e,CHP}$	Electricity production in combined heat and power plant (MWh)
$E_{e,use}$	Electricity usage (MWh)
$E_{h,CHP}$	Heat production in combined heat and power plant (MWh)
E_{hp}	Total purchase of district heating within the city boundary (MWh)
f_{em}	Marginal emissions factor for affected electricity (kg CO ₂ /MWh)
f_{ha}	Average emissions factor for district heating (kg CO ₂ /MWh)
f_i	Fuel emissions factor for the specific fuel i (kg CO ₂ /MWh _{fuel})
F_i	Fuel i for production of heat and electricity at the local district heating system (MWh)
$GHG_{affected\ production\ elsewhere}$	Greenhouse gas emissions from affected production elsewhere (kg)
GHG_{local}	Direct greenhouse gas emissions (kg)
GHG_{global}	Global greenhouse gas emissions (kg)
I_0	Initial investment in period zero (€)
n	Lifetime of the investment (year)
NPV	Net present value (€)
r	Cost of capital (interest) (%)
$\eta_{refe,i}$	Efficiency reference value for separate production of electricity with fuel i
$\eta_{refh,i}$	Efficiency reference value for separate production of heat with fuel i

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1 Introduction

This chapter gives a brief introduction to the thesis work and the research area. The aim and research questions are defined and Papers I-III are presented, together with co-author statements and a description of the research journey conducted.

Initiatives to reduce greenhouse gas (GHG) emissions are underway on several levels of society and among different stakeholders. One such initiative is standards for GHG inventories on different scales, such as for corporations or cities/regions. These standards focus on emissions within organisational or geographical boundaries. Purchases of energy carriers, such as electricity and district heating (DH), can constitute a large part of such GHG inventories. When valuing carbon dioxide (CO₂) emissions from purchased energy carriers, average emissions factors are often used and sometimes also contractual emissions factors. The standards emphasise the advantages of enabling aggregation of GHG inventories for smaller entities (e.g. cities) into GHG inventories for larger entities such as nations. Use of a GHG inventory for different decisions regarding GHG emissions reductions is advised. The GHG Protocol standards for corporate GHG inventories ('Corporate Standard'; WRI/WBCSD, 2013; WRI, 2015) and for city or regional GHG inventories ('City Standard'; WRI/C40/ICLEI, 2014) recommend that inventories be used for identifying reduction opportunities, setting, measuring and monitoring GHG reduction targets, building strategies for reducing GHG emissions, and measuring and monitoring the progress of a company, city or region regarding reduced emissions (when the word 'city' is used hereafter, it refers to 'city or region'). Furthermore, the Corporate Standard states that "The methods used to calculate and report scope 2 emissions [emissions from purchased electricity, steam and heat] critically impact how a company assesses its performance and what mitigation actions are incentivized" (WRI, 2015: 6).

A company can improve its GHG inventory by changing the amount of energy or the energy carrier it purchases. A city can improve its GHG inventory by similar changes within its geographical boundary. Furthermore, an energy company can be indirectly incentivised by how its products and other energy carriers are valued by the Corporate Standard and City Standard in terms of GHG emissions.

In addition, combined heat and power (CHP) technology, which is used e.g. in DH, can help reduce global GHG emissions in the supply and conversion of energy, since CHP production is more efficient than conventional separate production of electricity and heat. As the general reason for a GHG inventory is GHG emissions reduction, it is important that actions incentivised by the GHG inventory entail reduced global GHG emissions.

1.1 Aim and research questions

The aim of the thesis is to analyse how the use of common corporate and city GHG inventories for emissions reduction decisions can affect global CO₂ emissions when purchases or production of electricity and CHP-based DH are affected.

The hypothesis tested is: The use of corporate and city GHG inventories for CO₂ emissions reduction decisions can counteract reductions in global CO₂ emissions in the case of electricity and CHP-based DH.

The following three research questions are considered:

1. *How are measures affecting purchases of electricity and CHP-based DH incentivised by corporate and city GHG inventories and what is the impact on global CO₂ emissions?*
2. *How are production strategies in CHP-based DH systems incentivised by corporate and city GHG inventories and what is the impact on global CO₂ emissions?*
3. *Are there emissions reduction decisions that should not be based on corporate or city GHG inventories?*

These research questions are analysed, based on results from Papers I-III, as summarised in Table 1. In order to answer the research questions, a number of measures of a company purchasing electricity and DH and of a company producing CHP-based DH are analysed, as described in section 5.3. However, Papers I and II do not include an analysis of incentives in corporate or city GHG inventories and Paper III does not include an analysis of incentives in city GHG inventories. Therefore additional analyses, based on the results in all three papers, are reported in this thesis (further described in section 5.1.1).

Table 1. Overview of the papers (I-III) from which results are used to explore research questions 1-3

Research question	Paper
1	I, III
2	II, III
3	I, II, III

1.2 Scope and delimitations

The thesis is delimited to the incentive in corporate and city GHG inventories made according to the standards of the GHG Protocol (explained in Chapter 3) regarding use of electricity and DH from a CHP-based DH system (DHS) and the indirect incentive it gives to production of electricity and CHP-based DH. The incentive given in corporate or city GHG inventories are compared with the incentive given by a consequential analysis (further described in sections 5.2.3 and 5.8). The consequential analysis includes emissions from affected electricity production elsewhere due to changes in use or CHP production of electricity. Other market-mediated effects, such as emissions because of limited supply of bio-fuel, are not addressed in the consequential analysis in this thesis.

The company making a corporate GHG inventory (hereafter called ‘the reporting company’) is assumed to be a company that purchases electricity and DH for its own use. Incentives that the location-based and market-based scope 2 totals (section 3.1) of a corporate GHG inventory give to the reporting company and the producers (suppliers) of electricity and DH are studied. For the city GHG inventory, incentives that the territorial total and the BASIC total (section 3.2) give to the reporting city and the purchasers and the producers of electricity and DH in that city are studied. The GHG inventories and studied totals are described in Chapter 3 of this thesis.

A number of assumptions are made to deliberately limit some of the underlining conditions of the analysis, so that unnecessary complexity in the analysis can be avoided while keeping the focus on the primary subject. These assumptions are as follows:

- The available energy carriers for the reporting company to purchase are limited to electricity and DH.
- The studied changes in purchases and production of electricity cause negligible changes in the national grid average emissions factor for electricity.
- The entire DHS studied is located within the city for which the city GHG inventory is made (DH produced within the city equals DH used within the city and distribution losses).
- Total electricity use in heat-only boilers (HOBs) and CHP plants in a DHS is assumed not to change when production in a DHS changes.
- Electricity produced in the studied city is limited to electricity produced at the studied CHP-based DHSs.

1.3 Overview of appended papers

Paper I

Kristina Difs, Marcus Bennstam, Louise Trygg, Lena Nordenstam

Energy conservation measures in buildings heated by district heating - A local energy system perspective. *Energy* 35, 2010, pp. 3194-3203.

Paper I investigates the economic and CO₂ impact of energy efficiency measures in buildings heated by DH. The effects of three energy efficiency measures implemented in Linköping DHS are assessed: heat load control, attic insulation and electricity savings on lighting. All energy efficiency measures are assumed to change annual use of DH by 10 GWh. The results show that attic insulation entails the largest reduction in local CO₂ emissions, while electricity savings on lighting entail increased local CO₂ emissions due to increased production of DH. However, when affected CO₂ emissions elsewhere are also taken into account, the results show that electricity savings give the greatest reduction in global CO₂ emissions. Making electricity savings on lighting is shown to be the most profitable investment for the company making the investment and the DH company together.

Paper II

Lena Nordenstam, Marcus Bennstam, Louise Ödlund (formerly Trygg)

Considering investment resources when assessing potential CO₂ reductions of CHP - a case study. *Energy Procedia* 116, 2017, pp. 172-284.

Paper II analyses the impact of the assumption of unlimited/limited investment resources on assessment of the CO₂ emissions reduction potential of investments in existing CHP-based DHSs. When profitable CO₂ reductions are based on net present value (NPV) only, unlimited investment resources are implicitly assumed. In Paper II, the equivalent annual annuity ratio is used to rank investment alternatives when investment resources are limited. Four bio-fuelled alternative investments (one HOB and three CHP alternatives) in an existing CHP-based DHS are evaluated and the profitable reduction potential of local and global CO₂ emissions is assessed. The results show that the assumption of unlimited/limited investment resources could change the profitability ranking. An investment with positive NPV can also be considered to be insufficiently profitable when investment resources are limited. The results also show that it could be counterproductive for global CO₂ abatement to base investment decisions regarding CHP on effects on local CO₂ emissions.

Paper III

Lena Nordenstam, Danica Djuric Ilic, Louise Ödlund (formerly Trygg)

Corporate greenhouse gas inventories, guarantees of origin and combined heat and power production - Analysis of impacts on total carbon dioxide emissions. *Journal of Cleaner Production*, 186, 2018, pp. 203-214.

Paper III analyses how corporate GHG inventories, which include average and contractual emissions factors, and the European Union (EU) framework of guarantees of origin (renewable and high efficiency) and emissions disclosure of energy carriers can incentivise companies in their emissions reduction decisions when CHP-based DH is affected, and the effect it could have on global GHG emissions. This is done from the perspective of the reporting company (aiming to improve its GHG inventory) and from the perspective of the DH company (wanting to improve the average emissions factor of its product by changing production strategy). Average and marginal emissions factors for DH from two CHP-based DHSs are assessed. Changes in global CO₂ emissions due to changes in CHP electricity production strategy are also assessed. It is shown that the use of average and contractual emissions factors for energy carriers and attributional (section 5.2) corporate GHG inventories in climate decision-making concerning energy purchases can lead to an increase in global GHG emissions, as effects on emissions elsewhere are disregarded.

1.4 Co-author statements

In **Paper I**, Kristina Difs designed the study, collected input data for the buildings, analysed the results and wrote the paper. Marcus Bennstam had the main responsibility for the MODEST modelling. I contributed to the initial discussions about the aim of the study and the parameters that should be analysed. Together with the other co-authors, I also commented on the paper.

In **Paper II**, Marcus Bennstam was responsible for the MODEST modelling and economic calculations. He also participated in the first analyses of the results and provided comments on the paper. I conducted the final analysis and structured and wrote the paper. Louise Ödlund (formerly Trygg) commented on the paper.

In **Paper III**, I performed the calculations, analysed the results and wrote the paper. Danica Djuric Ilic and Louise Ödlund (formerly Trygg) commented on the paper.

1.5 Research journey

I am employed by Tekniska verken i Linköping AB (publ) (TvAB), where I am in charge of a team working with production optimisation of hydro power and DH, investment calculations, electricity trading, economic policy instruments, climate valuation of electricity and DH and other energy systems-related subjects. One of the areas in which I am particularly interested is the conditions for CHP production and driving forces for and against CHP production.

In 2008, I was appointed leader of a project that sought to identify how Linköping DHS should be developed. The project was run by TvAB in cooperation with Linköping University. Marcus Bennstam, energy strategist at TvAB and fellow industrial PhD student, carried out all the MODEST modelling and economic calculations and various experts at TvAB were engaged in different working groups developing cost and price input data for the modelling. When the TvAB project started, I was also offered the opportunity to enrol as an industrial PhD student at Linköping University. The idea was to combine the two tasks with mutual benefits.

Part of the early assignment in the TvAB project was to forecast future DH demand. One of the aspects that was taken into account was expectations on future energy efficiency measures at customers. This was the inspiration for Paper I, where the economic and CO₂ impact of energy efficiency measures in buildings heated by DH was analysed. Input data for the MODEST modelling in Paper I were taken from the TvAB project.

Later in the TvAB project, a number of alternative scenarios to lower the company's dependence on oil, secure its reserve capacity for heat production and cut costs were evaluated. Measures at customers and at TvAB were studied. In Paper II, four of the alternative bio-fuelled production investments (three CHP alternatives and one HOB) from the TvAB project and their impact on CO₂ emissions were analysed. One of the purposes was to analyse how the recurring assumption of unlimited investment resources affected results compared with an assumption of limited investment resources. Input data and optimisations used in Paper II were taken from the TvAB project.

At this point, analyses on the impact on local and global (total) CO₂ emissions of customers' energy efficiency measures and a DH company's production investment alternatives were made. However, it is customers who choose which energy carrier to use for heating and which energy efficiency measures to implement. In addition, customers' choices send important signals to their suppliers. It is well known among Swedish energy companies that corporate customers often ask for local average or contractual emissions factors of energy carriers when choosing which energy carrier to purchase and for monitoring their company's impact on CO₂ emissions. Thus, low average or contractual emissions factors are important also for their energy suppliers.

I found that the reason for this customer choice of emissions factors is most likely the standard of the GHG Protocol for corporate GHG inventories (or corresponding standards). In addition, contractual emissions factors originate from an EU framework. As this standard and the EU framework seem to have important impacts on customers' choices, it was of interest to study their incentives to customers and their indirect incentives to CHP-based production of DH, and how that could affect global CO₂ emissions. This was done in Paper III, using two typical DHSs and two geographical locations.

The GHG protocol also provides a standard for city (regional) GHG inventories. In the extended work reported in this thesis essay, the research conducted in Papers I-III was expanded to include analyses of incentives in the two GHG Protocol standards to customers, cities and producers of electricity and CHP-based DH, using cases (some) from all three papers.

2 The CHP technology and concerned markets

In this chapter, the CHP technology is briefly presented, including some of its characteristics. The markets in which electricity and DH are sold are then described. Finally, the use of renewable guarantees of origin in the European electricity market is presented.

2.1 CHP

CHP production is the co-generation of electricity and heat. Compared with separate production of electricity and heat, this is a more energy-efficient process as it utilises the excess heat from electricity production. The power-to-heat ratio of CHP plants varies, depending on production plant type and fuel use. A typical power-to-heat ratio for a new natural gas-fuelled CHP is 1.5, while a new CHP plant fuelled by forest chips can have a gross power-to-heat ratio of 0.4-0.6 (representing small-large plant capacity). If heat extracted through FGC is included, the ratio decreases (Nohlgren et al., 2014).

CHP technology is described in detail by Frederiksen and Werner (2013). In a CHP plant, most of the exergy (quality or available work of the energy) is first ‘shaved off’ as electricity. The remaining exergy and energy are then used to produce DH. In a thermodynamic comparison, Lowe (2011) likens the performance of a CHP plant to that of a virtual heat pump, but with more heat utilised per kWh electricity sacrificed in the CHP plant compared with a condensing power plant.

Studies have shown that changes in global CO₂ emissions can differ from changes in local emissions when DH demand or production strategies change in a CHP DHS (Åberg and Henning, 2011; Levihn, 2014).

2.2 Electricity and district heating markets

CHP production is part of both the electricity and DH markets. Some similarities and differences in the functions of these markets are outlined below.

Electricity and DH are both delivered through a mains system and are in general delivered at the same time as they are used. This distinguishes electricity and DH from many other products, which are stored in some quantity by the user for a shorter or longer time before they are used. In general, electricity and DH markets also differ from each other.

In Europe, the EU is working to create a single European electricity market. Transmission system operators in 34 European countries are working on the development of future common European rules for electricity trading, reliability and connection to the grid. Since the end of 2016, seven European power exchanges (involving 23 countries) cooperate in calculation of the hourly day-ahead electricity price (gross electricity price). This includes joint optimisation of the transmission capacity and production needed to balance the system. Furthermore, the EU requires unbundling of actors in the electricity market, whereby the electricity distribution company may not produce or sell electricity (EP, 2009a; ENTSO-E, 2016; Nordpoolspot, 2018a, 2018b; Paper III).

The gross electricity price is calculated based on the equilibrium point between the cumulative supply and demand curves for each hour, considering limitations in transmission capacity. The most expensive production needed to balance the system and the highest price that purchasers are willing to pay to meet the demand are both reflected in this price (NordPoolspot, 2018a). The price at the equilibrium point for electricity area 'Stockholm' (one of four electricity areas in Sweden) compared with the short-term variable costs for coal power and gas-fuelled power plants is shown in Figure 1. Joint optimisation of transmission capacity and production (which existed also before 2016, but involved fewer countries) means that the electricity price at the equilibrium point for electricity area 'Stockholm' often reflects the cost of coal condensing power, although only about 0.2% of electricity production within Sweden is produced in condensing power plants (SCB, 2018). There are also periods when electricity price in electricity area 'Stockholm' differs from the cost of coal condensing power. One example of peaking electricity prices in Sweden is the period December 2009-February 2010 (Figure 1). Because of extended revisions of Swedish nuclear power stations and lowered transmission capacities within Sweden, and between Sweden and surrounding countries, during that abnormally cold period, electricity reserve production within Sweden contributed to unusually high electricity prices in Sweden (SvK, 2010). The corresponding period one year later was periodically even colder and there were recurring problems with extended revisions and lowered transmission capacities, but to a lower extent (SvK, 2011). Spring, summer and autumn in 2011, 2012 and 2015 were 'wet periods', when large water flows increased hydro power production in Sweden and Norway and caused a fall in electricity prices in electricity area Stockholm (Figure 1), as electricity demand in Scandinavia was low and possible export capacity was insufficient to handle the surplus (Energiföretagen, 2018).

Figure 1. Weekly average electricity spot price for electricity area 'Stockholm' (one of four electricity areas in Sweden) and short-term variable costs for electricity based on coal condensing power (efficiency 35-46%) and natural gas power (efficiency 32-58%) (IPCC, 2007; Nohlgren, 2014; Syspower, 2018; Paper II).

There are more than 5000 DHSs in Europe. A few of these are connected by transit mains (about 20-160 km long). However, DH cannot be transported over long distances as efficiently as electricity. This is why DH markets tend to be local and more numerous. In the same way that the Swedish electricity system has a national transmission system operator, each DHS also requires a system operator whose role is to ensure e.g. that there is enough DH available to meet the demand at all times. A DH company often has many roles, e.g. as system operator, producer and distributor. A DH company can also trade DH with owners of connected DHSs and purchase heat from other producers, such as industries. Altogether, this means that the DH company is often responsible for the total mix of production in its DHS and the CO₂ emissions related to the DH (Gochenour, 2001; Werner, 2006; Andrews et al., 2012; Werner, 2017).

2.3 The use of renewable guarantees of origin in Europe

Through the Electricity Market Directive (EP, 2009a), all electricity suppliers in Europe are required to disclose to their customers the origin of the overall fuel mix in the electricity supply (share of coal, gas, nuclear, renewables or other source) and the environmental impact (CO₂ emissions and radioactive waste) resulting from production of the electricity they delivered in the preceding year. One of the objectives of electricity disclosure is to enable informed choices when purchasing electricity (EC, 2004). Renewable guarantees of origin (RE-GO), also imposed by the EU (EP, 2009b), can be used to verify the quantity of

electricity from renewable sources required for the electricity disclosure. Producers of renewable electricity receive electricity RE-GOs, which in turn can be sold to generate extra income.

Apart from being used in conjunction with electricity disclosure, RE-GOs are also bought and used for allocating CO₂ emissions to a company or a product. Brander and Ascuí (2015) describe this as purchasing a “contractual emissions factor”. According to Raadal (2013), ‘zero emissions’ is the prevailing interpretation of CO₂ emissions in electricity RE-GOs.

3 Corporate and city GHG inventories studied

In this chapter, the corporate and city GHG inventories studied are described and GHG inventory totals analysed in this thesis are presented.

The GHG Protocol provides several GHG accounting standards (GHG Protocol, 2017). The earliest of these, the ‘Corporate Accounting and Reporting Standard’ (Corporate Standard) (WRI/WBCSD, 2013; WRI, 2015), is the most commonly used for corporate GHG inventories and is the foundation on which many other standards, and governmental and non-governmental GHG programmes, are based. Development of the Corporate Standard was initiated and coordinated by the World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) in cooperation with companies and environmental groups. The Corporate Standard was first published in 2001 (Green, 2010).

Since 2014, the GHG Protocol also provides an accounting standard for GHG inventories for subnational regions (city, city district, municipality, county, etc. or a combination of areas). This standard, the ‘Global Protocol for Community-scale Greenhouse Gas Emissions Inventories – An Accounting and Reporting Standard for Cities’ (City Standard), was developed jointly by the WRI, the C40 Cities Climate leadership Group (C40) and the International Council for Local Environmental Initiatives (ICLEI-Local Governments for Sustainability) (WRI/C40/ICLEI, 2014).

The Corporate and City Standards list several examples of when a corporate or city GHG inventory can be used for emissions reduction decisions. According to these standards, the information in GHG inventories can be used to identify reduction opportunities, to set, measure and report on GHG targets, to build a GHG abatement strategy and to monitor progress on GHG abatement (WRI/WBCSD, 2013: 3, 11; WRI/C40/ICLEI, 2014: 19, 35).

The parts of the Corporate Standard and City Standard that relate to the production and use of electricity and DH, and which are relevant to the analysis in this thesis, are described in the following sections.

3.1 Corporate GHG inventory

A corporate GHG inventory carried out according to the Corporate Standard has an organisationally defined boundary and focuses mainly on emissions sources owned or controlled by a company (scope 1) (direct emissions) and emissions from production of the company's purchased electricity, heat and cooling (scope 2) (Figure 2). Since 2015, two totals are required for Scope 2. One is the 'location-based' total, in which emissions from regional/national production averages are used as emissions factors (Table 2). The other required scope 2 total is a 'market-based' total, in which contractual emissions factors, such as RE-GOs, are primarily used (Table 2). Scope 3 is an optional reporting category and may include optional upstream and downstream emissions that are not included in scope 1 or 2 (WRI/WBCSD, 2013; WRI, 2015). A principal function of the inventory is to allocate responsibility for GHG emissions, and avoidance of double counting is important.

In a corporate GHG inventory, purchases of electricity and DH affect the location-based and market-based scope 2 totals. It may also affect the scope 3 total, if the reporting company chooses to report scope 3 emissions. In this thesis, the incentives in the location-based and market-based scope 2 totals (Table 2) concerning CO₂ emissions are analysed (further described in section 5.7).

Figure 2. Emissions included in the Corporate Standard (Schaltegger and Csutora, 2012; WRI/WBCSD, 2013).

3.2 City GHG inventory

A city GHG inventory carried out according to the City Standard (WRI/C40/ICLEI, 2014) has a geographically defined boundary. The City Standard focuses on scope 1, scope 2 and scope 3 emissions occurring due to activities taking place within a geographically defined subnational area (city, city district, municipality, county, etc. or a combination of areas). Contractual emissions factors are not used in a city GHG inventory, but can be reported separately (WRI/C40/ICLEI, 2014).

The City Standard (WRI/C40/ICLEI, 2014) requires comprehensive reporting, including reporting of seven GHGs (Table 2) and CO₂-equivalents (CO₂eq) per sector (stationary energy; transportation; waste; industrial process and product use; agriculture, forestry and other land use) and subsector. In addition, the following totals are required:

- *Per scope totals.* Scope 1 (territorial): emissions from within-boundary sources; scope 2: emissions from grid-supplied energy sources; and scope 3: emissions from outside-boundary sources. The City Standard states that a summary of territorial (scope 1) totals of several geographical areas, whose inventory boundaries do not overlap geographically, will therefore be consistent with national-level GHG reporting.
- A ‘city-induced’ total that includes selected scope 1, 2 and 3 emissions sources (the ‘key emitting sources’). There are two options: BASIC and BASIC+. (BASIC+ is more comprehensive and is coordinated with the International Panel on Climate Change (IPCC) guidelines for national reporting.)

In a city GHG inventory, purchases and production of electricity and DH can affect several totals, such as sector, scope 2, scope 3, BASIC and BASIC+ totals. In this thesis, incentives in the territorial total and the BASIC total (Table 2) are studied. The analysis is delimited to effects on CO₂ emissions of purchases and production of electricity and DH, as further described in section 5.7.

Table 2. Emissions regarding purchases or production of electricity and district heating (DH) which, according to the standards of the greenhouse gas (GHG) Protocol, are included in the GHG inventory totals analysed in this thesis and the standards' ranking of emissions factors (WRI/WBCSD, 2013; WRI/C40/ICLEI, 2014: 42-43; WRI, 2015). Emissions and parameters used in the analysis in this thesis are presented in section 5.7

Emissions and choice of emissions factors	GHG
Corporate GHG inventory	
<i>Location-based total (scope 2):</i>	
Emissions from production of the energy carrier purchased by the reporting company. Upstream emissions are not included. Firstly regional grid average emissions and secondly national grid average emissions.	CO ₂ or CO ₂ equivalent (CO ₂ eq)
<i>Market-based total (scope 2):</i>	
Emissions from production of the energy carrier purchased by the reporting company. Upstream emissions are not included. First, contractual emissions factors for 'energy attribute certificates' (e.g. RE-GO); then other types of contracts; utility emission rates; subnational/national residual mix; and last, regional/national grid average emissions.	CO ₂ or CO ₂ eq
City GHG inventory	
<i>Territorial total (scope 1):</i>	
"GHG emissions from sources located within the city boundary"	CO ₂ , methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride, nitrogen trifluoride and CO ₂ eq
<i>BASIC total (scope 1 and 2):</i>	
Scope 1: "emissions from fuel combustion within the region, but not emissions from energy generation supplied to the grid".	CO ₂ , methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride, nitrogen trifluoride and CO ₂ eq.
Scope 2: "emissions from grid-supplied energy consumed within the city boundary". Firstly regional grid average emissions and secondly national grid average emissions. Upstream (scope 3) emissions, such as transmission and distribution losses from grid-supplied energy usage or emissions from mining and transporting, are not included.	

4 Previous research

In this chapter, the main findings reported in some previous studies regarding GHG inventories and emissions disclosure are presented.

Within the broad term carbon accounting, researchers in different fields have studied numerous layers and aspects of carbon accounting on molecular, national, project, company and product scale (see reviews by Ascui and Lovell, 2011; Stechmesser and Guenther, 2012; Ascui, 2014; Hahn et al., 2015). The research areas relevant to this thesis are corporate GHG inventories, GHG inventories for geographical areas and emissions disclosure for products.

4.1 Corporate GHG inventory

According to Brander and Ascui (2015), the most common form of carbon accounting on company scale is an inventory of a company's physical GHG emissions, carried out according to a protocol such as the Corporate Standard. Research by Luo et al. (2012) has shown that voluntary disclosure of the results of corporate GHG inventories is more common for larger companies and companies in GHG-intensive sectors. Reasons for voluntary disclosure can include legitimacy seeking, as found by Hrasky (2011) and Pellegrino and Lodhia (2012). Liesen et al. (2015) have shown that external stakeholder pressure can also affect companies' willingness to disclose. According to Gibassier and Schaltegger (2015), corporate GHG inventories are used internally in GHG management.

In research on the importance of accuracy, consistency and certainty in different fields of carbon accounting, Bowen and Wittneben (2011: 1029) have found that credibility is the highest ranked aspect for organisational GHG accounting. For companies, "an apparently high degree of certainty in their carbon reporting requirements" contributes to their credibility. For external reporting, consistency in measurements is important, as it contributes to fairer competitive conditions between companies. Bowen and Wittneben (2011: 1033) also highlight the challenge of accomplishing actual reductions in GHG emissions. They recommend the use of other methods, such as technological standards or promotion of investment in renewables and energy efficiency measures, rather than GHG inventories.

Green (2010) provides a comprehensive description of development of the Corporate Standard through “entrepreneurial authority” where, in the absence of international political agreements, the WRI and WBCSD coordinate cooperation between several corporations, non-governmental organisations (NGO), governments and others. The benefits of participating in the development of rules are acknowledged by Green (2010) and Andrew and Cortese (2011), with the latter expressing concern for the corporate impact, since voluntary standards are likely to influence future regulations. Green (2010) has also described the benefits of the early adopters in appearing proactive in emissions reductions.

Less research has been performed about incentives in corporate GHG inventories. However, Brander (2017) compares the incentive in a corporate GHG inventory with that provided by methods that take into account market-mediated emissions effects of limited supply of bio-fuel, in the case where natural gas is replaced with bio-fuel for heating purposes. According to the results, the corporate GHG inventory does not capture the full consequences of the fuel change with regard to global GHG emissions. Furthermore, an attributional-consequential distinction, which is applied in life cycle assessment (LCA) (see section 5.2.1), is suggested by Brander and Ascui (2015) to be used for corporate GHG inventories.

Like Brander (2017), the research presented in this thesis also compares incentives in a corporate GHG inventory with incentives in a consequential analysis. However, in this thesis purchases of electricity and CHP-based DH are studied and the market-mediated emissions effects of such purchases are analysed.

4.2 GHG inventories for geographical areas

Production-based and consumption-based accountings are two basic principles of allocating responsibility for GHG emissions between geographical areas. In production-based accounting, which is used in international negotiations on climate change and IPPC, emissions are attributed to the geographical area where production takes place and where the emissions occur (IPCC, 2006; Afionis et al., 2017). This principle is also called territorial accounting, which corresponds to the territorial total included in a city GHG inventory (described in sections 3.2). According to Peters (2008), one of the criticisms of production-based accounting is that it could incentivise a nation or region to fulfil its national/regional GHG target by importing products instead of producing them, thereby causing carbon leakage instead of actual reductions.

In consumption-based accounting, emissions during production and transport of products are attributed to the geographical area where the product is used. This principle is similar to how energy carriers are included in the BASIC total in a city GHG inventory (described in section 3.2). When a consumption-based inventory is used, the potential risk of carbon leakage is avoided. However, the incentive for producers to find more efficient production methods with

lower CO₂ emissions is reduced (Munksgaard and Pedersen, 2001). Afionis et al. (2017) present a compilation of the pros and cons of consumption-based accounting. A number of methods for shared producer-consumer responsibility have been suggested (e.g. Bastion et al., 2004; Peters, 2008).

This thesis complements previous research on GHG inventories for geographical areas by comparing incentives in a territorial total and a BASIC total of a city GHG inventory (Table 2) with the incentives in a consequential analysis, when purchases or production of electricity or CHP-based DH are affected.

4.3 Emissions disclosure of products

Emissions disclosure of products can be used as a complement to emissions regulations and emissions taxes to reach environmental goals. This is based on the fundamental principle of economic theory that customers have the power to affect products, and the behaviour of companies, by choosing what to buy and from which supplier. Standardised information about the environmental assets of a product (whether it is good or bad), presented in an environmental disclosure, aims to help customers make an informed choice. By increasing demand for products with low GHG emissions and decreasing demand for products with high GHG emissions, customers can influence producers to put products with lower climate impact on the market (Rezabakhsh et al., 2006; Willstedt and Bürger, 2006; Delmas et al., 2009).

Environmental disclosure or emissions disclosure of products can be mandatory, such as the European system of electricity disclosure described in section 2.3. It can also be voluntary, used for marketing purposes. Standards for voluntary environmental or GHG disclosure of products are provided by the EPD[®] (Environmental Product Declaration) (EPD, 2015) and the GHG Protocol (Product Life Cycle Accounting and Reporting Standard) (WRI/WBCSD, 2011), among others. The standards provided by the EPD[®] and the GHG Protocol are attributional (see section 5.2.1).

In addition to the reasons for emissions disclosure described above, a reporting company making a GHG inventory needs information from its energy suppliers about average emissions factors for its purchased electricity and DH. A reporting city needs corresponding information about the energy being purchased within its geographical boundary. This kind of emissions disclosure of energy carriers is regulated by the standard of the corporate or city GHG inventory. The Corporate Standard and the City Standard require attributional emissions factors (and sometimes contractual emissions factors) on purchases of electricity and DH (WRI/WBCSD, 2013; WRI/C40/ICLEI, 2014; WRI, 2015) (Table 2).

Tillman (2000) lists several arguments for using attributional data in emissions disclosure of products. One argument is that common rules must be agreed upon and, if a consequential approach were used, it would be difficult to reach consensus on the marginal process and its data. Another argument is that additivity is important for producers when new products are produced in a process where other products are used. In addition, marginal processes may not be known.

The research presented in this thesis focuses on the incentives given to purchasers and producers of products, and cities where the products are used, when attributional data are used in emissions disclosure of the products. The products studied here are electricity and CHP-based DH and the context where the attributional data is used is corporate and city GHG inventories.

4.3.1 *RE-GOs*

Previous research about electricity RE-GOs deals e.g. with their credibility. For example, Winther and Ericson (2013) show that Norwegians believe they do not have to purchase RE-GOs in order to get renewable electricity, as the Norwegian public knows that electricity produced within Norway is dominated by hydro power. At the same time, others question the emissions reduction benefits of purchasing hydro RE-GOs imported from Norway, as they believe it will not result in more renewable electricity production (Mulder and Zomer, 2016; Hufen, 2017). On analysing the impact of using RE-GOs in a market-based total of a corporate GHG inventory (described in section 3.1), Brander et al. (2018) conclude that purchase of an electricity RE-GO is less likely to induce a corresponding increase in production of renewable electricity because of the large surplus of RE-GOs on the market and the lack of additionality requirements for RE-GOs.

This thesis adds to previous research by studying the incentive given by a corporate GHG inventory to change from heat from electricity to CHP-based DH (or vice versa) and to lower or increase purchases of electricity and CHP-based DH, when electricity RE-GOs are used for purchased electricity. The use of concrete examples in this thesis also complements the more theoretical reasoning on the impact of electricity RE-GOs reported by Brander et al. (2018).

5 Method

In this chapter, methods used in Papers I-III and the additional analyses made in this thesis are presented. The chapter presentation starts with an initial overall method description and an overview of the origin of results presented in this thesis (Papers I-III or the thesis itself).

5.1 Overall description

The incentives in four GHG inventory totals are analysed. For the corporate GHG inventory, incentives in the location-based and market-based scope 2 (sections 3.1 and 5.7) for a reporting company when purchasing electricity and CHP-based DH, and the indirect incentives this gives to the DH company when producing electricity and CHP-based DH, are analysed. For the city GHG inventory, incentives in the territorial total and the BASIC total (sections 3.1 and 5.7) for the reporting city and for companies' purchases and production of electricity and DH within the city boundary are analysed. A number of measures are analysed, as presented in section 5.3. Measures improving (lowering) a GHG inventory total are considered to be incentivised by that GHG inventory total. Measures worsening (increasing) a GHG inventory total are considered to be incentivised against.

A consequential method is used for assessing how different measures incentivised for or against in an attributional GHG inventory affect global CO₂ emissions. (Attributional and consequential methods are described in section 5.2.) Measures lowering global CO₂ emissions are considered to be incentivised by the consequential method and measures increasing global CO₂ emissions are considered to be incentivised against. The measures of companies purchasing or producing electricity and DH, which are used to investigate effects on GHG inventory totals and global CO₂ emissions, are described in section 5.3. Each measure constitutes a scenario.

In the consequential analysis, the implemented measures are assumed to affect the European electricity system and/or a DHS, which are described in section 5.4. In order to investigate any differences between inventories carried out in a nation where electricity production within the nation is considered CO₂-lean (Sweden) and a nation where electricity production is CO₂-

rich (Germany), a Swedish location and a German location are used for each combination of measure and GHG inventory total.

Optimisations and calculations made in order to assess how each measure affects the DH and electricity systems are described in section 5.5. The economic valuations made for the investment scenarios (B1 and B2 in section 5.3) are described in section 5.6. Parameters and methods used for assessing how measures of purchases and production of electricity and DH affect the GHG inventory totals studied are presented in section 5.7. In section 5.8, the method used for the consequential analysis is described. Input data for economic optimisations and emissions assessments are shown in section 5.9.

5.1.1 Overview of the sources of results

Some of the results presented in this thesis are taken from Papers I-III and some are the outcome of new analyses made in the thesis. An overview of the source of results for each scenario is given in Table 3. (Scenarios are described in section 5.3.)

Table 3. Overview of the source of optimisations and assessments leading to the results presented in this thesis. (Scenarios are described in section 5.3.)

Scenarios	Investments*, economic measures	Production of DH and electricity	National average emissions factors for electricity	Effects on					
				Average emissions factors for DH (before and after implementation of measures)	Location-based total	Market-based total	Territorial total	Basic total	Global CO ₂ emissions
A1, A2	--	PI*	PIII	T	T	T	PI	T	PI
B1, B2	PII	PII*	PIII	T	T	T	PII	T	PII
C1 _{bio} , C2 _{bio} , C3 _{bio} , C1 _{gas} , C2 _{gas} , C3 _{gas}	--	PIII	PIII	before: PIII after: T	T	T	T	T	T
C4 _{bio} , C4 _{gas} , C5 _{bio}	--	PIII	PIII	before: PIII after: PIII	T	T	T	T	PIII

DH = district heating, PI = Paper I, PII = Paper II, PIII = Paper III, T = this thesis

* = optimisation

5.2 Attributional and consequential methods

5.2.1 Methods used in Life Cycle Assessment

Life Cycle Assessment is a commonly applied tool for assessing the environmental impacts of products. LCA can be used to assess the use of resources and the environmental impact during the life cycle of products. Upstream activities (extraction, treatment and transportation of raw material), production and downstream activities (use and waste management) for the product are included (Figure 3) (Finnveden et al., 2009; Schaltegger and Csutora, 2012).

Figure 3. Life stages included in life cycle analysis (EPA, 1993, 2006)

There are essentially two types of LCA methods, attributional and consequential (Finnveden et al., 2009). An attributional LCA describes all environmentally relevant physical flows to and from a life cycle and is based on average data. Attributional LCAs are used for allocating responsibility for environmental effects between products, companies or geographical areas. A consequential LCA, on the other hand, describes the change in environmentally relevant flow/s caused by an act. This means that only flows that are affected by the decision at hand are included. In consequential LCAs marginal data are used (Finnveden et al., 2009).

There is a debate in the LCA literature about the purpose and use of attributional and consequential LCAs. According to Ekvall et al. (2005) both types of LCA can be used for learning purposes and for decision-making. According to Wenzel (1998) and Weidema (2003), LCAs are essentially performed in order to inform decision making. Tillman (2000) agrees that decision making is central to LCA and mentions examples such as influencing market behaviour, identifying improvement possibilities and choosing among alternative acts. She suggests that consequential LCA should be used when comparing alternative actions and that attributional LCA should be used for emissions disclosure of products and for the first stages of decision making, such as learning and identifying reduction opportunities. Plevin et al. (2013) and Brander and Ascui (2015) suggest that only consequential LCA should be used

for decision making, as decisions based on attributional LCA can result in undesirable consequences (increased emissions). According to Ekvall et al. (2016), when LCA is used for decisions on improvements, comparisons and purchases of products, as well as labelling of products (EPD[®], carbon footprint), the LCA results are used as decision support. They argue that this is the case also when LCA is used in policy making for identifying improvement potentials and for policy development. Ekvall et al. (2016) conclude that a consequential LCA should therefore be used for these applications. According to Ekvall et al (2016), LCAs are not used as decision support when used for monitoring and reporting on products and policy.

Limitations

Both attributional and consequential LCAs have limitations. As an attributional LCA “does not reflect any marginal effects” (Ekvall et al., 2005), basing decisions on the result of an attributional LCA risks causing unintended increases in emissions (Plevin et al., 2013; Brander and Ascui, 2015). Furthermore, according to Ekvall et al. (2005), the choice of system boundary is not unequivocal for attributional LCAs. This means that for purchased electricity, technology averages, producer averages, regional averages, national averages etc. can be used, which in turn can lead to differing results. Another source of differing results of an attributional LCA, according to Ekvall et al. (2005), is when allocating emissions between multiple products (such as electricity and DH produced in a CHP plant), as there are several allocation methods to choose between.

One of the limitations in consequential LCA is lack of completeness, as it is often impossible to include all effects of an action (Ekvall et al., 2005; Plevin et al., 2013). According to Ekvall et al. (2005), large uncertainties are likely to be associated with the results of consequential LCAs. As it can be difficult to identify and agree on the marginal effects, results can differ depending on choices made (Tillman, 2000; Plevin et al., 2013). Tillman (2000) also claim that a consequential LCA can be more difficult to perform, since more data are needed. According to Weidema (2003) and Thomassen et al. (2008) the data required for a consequential LCA can be similar or less than those required for an attributional LCA as the consequential LCA includes only processes which are affected by the change.

Precision, accuracy and relevance

According to Brandão et al. (2014) there are uncertainties in the form of precision and accuracy (Figure 4) in both attributional and consequential LCAs. When comparing the two LCA methods, they state that attributional LCAs can be said to be more precise than consequential LCAs, as it is easier to identify correct average emissions factors than correct marginal emissions factors. On the other hand, as effects on emissions elsewhere are included in consequential LCAs, but not in attributional LCAs, they state that attributional LCAs can be said to be less accurate than consequential LCAs. Weidema (2009) also discusses uncertainties in attributional and consequential LCAs. He states that “uncertainty addresses the reliability of our measurement” and stresses the importance of relevance. He concludes “When we are deciding how to measure what we look for, it is irrelevant how precisely we

can measure what we do not look for” (Weidema, 2009). Even though average data can be determined with great precision, use of marginal data is more relevant when assessing the consequence of a decision, according to Weidema (2009).

Figure 4. Illustration of precision and accuracy. The left target shows an example of high precision and low accuracy. The right target shows a case with higher accuracy, but lower precision, compared with the left target. (Brandão et al., 2014.)

Use of marginal and incremental data in consequential analysis

Azapagic and Clift (1999) and Ekvall et al. (2016) recommend that marginal and incremental data be used to model changes in affected production in consequential analyses. According to Azapagic and Clift (1999), marginal data should be used when the change in a production system is very small (example A in Figure 5), incremental data should be used when the change is substantial (examples B and C in Figure 5) and average data should be used for a complete change (example D in Figure 5). It can be noted that if incremental data are used for very small changes (example A in Figure 5), the average of the incremental data is the same as the average of the marginal data. In addition, the average of incremental data for a total change is the same as the average of the total data (Ekvall et al., 2016).

Figure 5. Marginal, incremental and total data on an affected production system where lowered production first affects production z, then production y and lastly production x.

5.2.2 Method used in corporate and city GHG inventories

Corporate GHG inventories are essentially attributional (WRI/WBCSD, 2013; Brander and Ascui, 2015) and this is also the case for city GHG inventories conducted according to the City Standard (WRI/C40/ICLEI, 2014). In general, average emissions factors are used. However, according to the Corporate Standard, contractual emissions factors are preferable in the market-based total (Table 2) (WRI/WBCSD, 2013). Brander and Ascui (2015) argue that the inclusion of contractual emissions factors in the market-based total differs from the requirement of an attributional method because of the lack of ‘physical relationship’. One of the purposes of corporate GHG inventories is to distribute the responsibility for emissions between companies, while one of the purposes of city GHG inventories is to distribute the responsibility between geographical areas. The Corporate Standard also emphasises the importance of avoiding double counting.

5.2.3 Method used here for assessing impact on global CO₂ emissions

A consequential approach is applied in Papers I-III and in section 5.8 of this thesis when assessing the impact of different measures on global CO₂ emissions. The energy system studied consists of two sub-systems, a local DHS and the European electricity system, schematically presented in Figure 6. The CHP plant and companies using electricity and DH are part of both the local DHS and the European electricity system. The environment of the energy system consists of much more than is shown in Figure 6, such as laws and regulations, fuel prices and also standards for voluntary corporate and city GHG inventories. In Papers I-III and in this thesis, the consequential analyses include changes in emissions from electricity production elsewhere. Marginal effects, causing changes in global CO₂ emissions, can also occur in other respects, such as through changed use of bio-fuel. Another fuel can be the marginal fuel if supply of bio-fuel is limited. Furthermore, material displacements or substitutions can be caused by increased production of bio-fuel (Brander, 2017). However, other marginal effects, apart from changes in emissions from electricity production elsewhere, are not included in the consequential analysis in Papers I-III or in this thesis.

Figure 6. Schematic representation of the energy system studied in Papers I-III and in this thesis and part of its environment. DH = district heating, HOB = heat-only boiler, CHP = combined heat and power, NGCC = natural gas combined-cycle plant.

5.3 Implemented measures

The implemented measures considered in the analysis, each representing a scenario, are listed in Table 4. Effects of energy efficiency measures are studied in Paper I, from which two measures are used in this thesis (A1 and A2). From Paper II, two out of four optional investments studied are used in this thesis (B1 and B2). The other measures in Table 4 are taken from Paper III. For measures $C1_{bio}$ - $C3_{bio}$ and $C1_{gas}$ - $C3_{gas}$, opposite measures are also studied.

For each group of measures (or scenarios), there is a reference scenario ($A0$, $B0$, $C0_{bio}$ and $C0_{gas}$) where no energy efficiency or production measure is implemented. In scenarios $C0_{bio}$ and $C0_{gas}$, CHP electricity production is fully utilised. For measures that affect changes in DH demand, time-dependent profiles are used (Figure 7). The difference between profiles P:A1 and P:Cx is that profile P:A1 only includes changes in outdoor temperature-dependent DH demand, while P:Cx also includes changes in heating of tap water (Figure 7). As indicated by profile P:A1 in Figure 7, the reduction in electricity use due to replacement of appliances is assumed not to contribute to an increase in use of DH during the warmest part of the year. For

decreased electricity use in measures $C1_{bio}$ and $C1_{gas}$ no profile is defined, since no time dependence is assumed for average emissions factors for electricity (used in GHG inventory totals) or marginal emissions factors for electricity (used in consequential analysis). In reality, however, marginal emissions factors for electricity differ over time, as indicated in Figure 1.

Table 4. Different scenarios with implemented measures for which effects on greenhouse gas (GHG) inventory totals and global CO_2 emissions are studied in this thesis. Opposing measures to $C1_{bio}$ - $C3_{bio}$ and $C1_{gas}$ - $C3_{gas}$ are also studied (Papers I-III). (Profiles are shown in Figure 7) DH = district heating, DHS = DH system, CHP = combined heat and power, HOB = heat-only boiler, NGCC = natural gas combined-cycle plant, SCOP = seasonal coefficient of performance

Scenario	Implemented measure	Research question
<i>Linköping DHS (described in section 5.4.2)</i>		
A1	Attic insulation, 10 GWh decrease in DH demand (profile P:A1)	1, 3
A2	Electricity savings by replacing appliances (lighting, refrigerators and freezers), 10 GWh increase in DH demand (Profile P:A2)	1, 3
B1	Construction of a new bio-fuelled CHP plant	2, 3
B2	Construction of a new bio-fuelled HOB plant	2, 3
<i>Bio-fuelled (bio) DHS and natural gas-fuelled (gas) CHP-based DHS (described in section 5.4.3)</i>		
$C1_{bio}$, $C1_{gas}$	Decrease in electricity use of 10 GWh	1, 3
$C2_{bio}$, $C2_{gas}$	Replacing use of 10 GWh DH (profile P:Cx) with 10 GWh electricity	1, 3
$C3_{bio}$, $C3_{gas}$	Replacing use of 10 GWh DH (profile P:Cx) with heat from an electricity-run heat pump, SCOP 4.0	1, 3
$C4_{bio}$, $C4_{gas}$	No electricity is produced	2, 3
$C5_{bio}$	Electricity production in the CHP plant is lowered to the extent that production of heat at the HOB is minimised	2, 3

Figure 7. Profiles of changes in district heating (DH) demand over a year used in scenarios A1, A2, C2_{bio}, C3_{bio}, C2_{gas} and C3_{gas} (see Table 4 for explanation of scenarios). The value to the extreme left represents the day with the highest total heat demand in the DH system, after which total heat demand decreases. The day of the year with the lowest total heat demand is shown on the extreme right.

5.4 Energy subsystems affected

The energy system studied is assumed to consist of two sub-systems (Figure 6): the European electricity system and one local DHS (Linköping DHS, a bio-fuelled DHS or a natural gas-fuelled DHS). These sub-systems are described below.

5.4.1 European electricity system

The European electricity system is assumed to work like today (described in section 2.2). A common economic optimisation of electricity production units and transmission capacity is assumed, so production plants with the lowest variable costs are used to meet electricity demand whereby marginal electricity production comes from the last plants needed to meet the electricity demand (see section 2.2). As it is difficult to assess exactly marginal electricity production, two alternative marginal productions are assumed, coal power plants and natural gas combined-cycle (NGCC) plants. This use of alternative scenarios in a consequential analysis in order “to understand the range of potential environmental outcomes” when the exact marginal value is difficult to identify follows the reasoning by Plevin et al. (2013).

5.4.2 Linköping DHS

The DHS in the Swedish city of Linköping is used as the case study in Papers I and II. Linköping has around 150 000 inhabitants and is situated 200 km south-west of Stockholm. The municipality-owned company TvAB owns and manages the DHS in Linköping.

At the time of the studies reported in Papers I and II, annual production of DH in Linköping was about 1600 GWh and maximum heat demand was about 500 MW. Annual electricity production in the CHP plants was about 350 GWh. The DH base production at that time comprised energy recovery from household and industry waste at Gärstad CHP plant, which had four boilers and two steam turbines (Figure 8a). Mid-merit production for Linköping DHS takes place at the Kraftvärmeverket CHP plant, where three boilers are jointly connected to three steam turbines (Figure 8a). A number of oil-fuelled HOBs serve as peak and reserve plants for heat production. A 30-km-long transit main connects the DHS of Linköping with the DHS of Mjölby-Svartådal Energi AB in Mjölby, the production system which consisted of bio-fuelled and oil-fuelled HOBs at the time of study (Figure 8a). Production in the two DHSs is co-optimised on a daily basis. Although heat demand must always be met, electricity is produced only to the extent that it is profitable. Electricity production in the CHP plants is essentially limited by heat demand, although some electricity production in condensing mode is possible. Electricity produced is sold on the electricity spot market described in section 2.2 (TvAB, 2009; Paper II).

Figure 8. (a) Technical data on existing district heating (DH) production plants in the Linköping-Mjölby DH system (DHS) at the time of the studies reported in Papers I and II (TvAB, 2009; Paper I; Paper II). (b) Capacities and efficiencies used in the assumed DHS based on bio-fuelled combined heat and power (CHP) and on natural gas-fuelled CHP (TvAB, 2009; Nohlgren, 2014; EC, 2015; GE, 2017; Paper III). FGC = flue gas condensation.

As described earlier, two locations are studied in this thesis work. Although Linköping DHS is located in Sweden, in the analysis of how location affects GHG inventory totals and global CO₂ emissions it is used in a Swedish and a German location. In order to concentrate and facilitate analysis of the GHG inventory totals and global CO₂ emissions, the DH demand is assumed to be the same regardless of whether the DHS is located in Sweden or Germany.

5.4.3 *Bio-fuelled and natural gas-fuelled CHP-based DHSs*

Paper III presents assessments for two general CHP-based DHSs (Figure 8b). Base production of DH in the bio-fuelled DHS (Figure 8b) is assumed to come from a bio-fuelled regular back-pressure steam turbine plant. Oil-fuelled HOBs are assumed to serve as peak and reserve plants for heat production. According to Werner (2017), this is a typical CHP-based DHS in Sweden.

In the natural gas-fuelled DHS (Figure 8b), a natural gas-fuelled CHP plant is assumed for base production of DH and natural gas-fuelled HOBs are assumed to serve as peak and reserve plants for heat production. This kind of DHS is more common in Germany (AGFW, 2017). The natural gas-fuelled CHP plant is assumed to be a NGCC-CHP plant similar to that in Gothenburg (Nohlgren et al., 2014; GE, 2017).

According to Andrews et al. (2012), CHP plants are often dimensioned to cover about half of peak heat demand. CHP plants are more expensive to invest in than HOBs. Therefore HOBs are often used for shorter operating hours, such as heat peak or reserve production. In this thesis, CHP capacities which provide about half the peak heat demand for the assumed demand and duration curve are used (Figure 8b).

Each CHP plant is assumed to consist of two similar units with separate maintenance periods. Regardless of CHP capacity and load, the efficiencies shown in Figure 8b are assumed. Inaccessibility of 4 and 2 % (due to e.g. operating problems) is assumed for the bio-fuelled CHP and natural gas-fuelled CHP, respectively. The CHPs are assumed not to be equipped for condensing mode, so electricity production is limited by the demand for DH.

A duration curve used by TvAB is assumed when defining heat demand for the 365 time periods of the year (see section 5.5.2). An annual heat demand of 1000 GWh, including 11% distribution losses, is assumed (TvAB, 2017). In the analysis of how location affects GHG inventory totals and global CO₂ emissions, these studied DHSs are used in a Swedish and a German location. In order to concentrate and facilitate the analysis of the GHG inventory totals, the DH demand is assumed to be the same regardless of the country in which the DHS is located.

5.5 Energy system optimisations and calculations

The optimisation model MODEST (Model for Optimisation of Dynamic Energy Systems with Time-dependent components and boundary conditions) is used for economic optimisations in Papers I and II. For energy system calculations, where no economic optimisation is needed, a calculation sheet developed by TvAB (TvAB, 2017) is used. By using these models, incremental data (see section 5.2.1), are assessed for production in the DHSs studied (sections 5.4.2 and 5.4.3).

5.5.1 Optimisation model MODEST

The optimisation model MODEST is designed to model and optimise investments and operations of energy systems (Henning, 1998; Henning, 1999; Gebremehdin, 2003). Linear programming is used to find the solution with the lowest present value of future system costs. Future system costs include costs and revenues of operation, and capital costs of investments for meeting a certain energy demand. Costs include e.g. fuel, fuel taxes, maintenance and capital costs for new investments. Revenues include e.g. income relating to electricity produced and sold. Input data such as energy demand, capacities and prices can be varied over time using a flexible time division, where each year can be divided into up to 99 seasons, each of which in turn can be divided into 99 or less diurnal periods. These periods can be used for describing variations in e.g. heat demand or electricity prices. MODEST has previously been used for different studies on more than 50 DHSs (e.g. Karlsson et al., 2009; Djuric Ilic et al., 2012).

As Linköping DHS is a complicated system, with several CHP plants and fuels, MODEST is used for economic optimisations of this DHS. In Paper I, MODEST is used to optimise the operation of the DHS studied (production of electricity and DH) before and after implementing energy efficiency measures with predetermined scale and distribution. In Paper II, MODEST is used to find the optimal operation before investments and then the optimal magnitude of each investment together with the optimal operation.

A model is a simplified description of reality. As MODEST is based on linear programming, it cannot take into account minimum partial loads or starting costs (for warming up or increased maintenance costs). Furthermore, some policy instruments (e.g. fuel taxes) should be calculated based on monthly data, but MODEST optimises each diurnal period, which does not reflect whole months. However, as such differences occur in each scenario, including the reference scenario, they partly cancel each other out when a scenario is compared with the reference scenario. The results of the optimisations made for Papers I and II were thoroughly checked and compared against other similar calculations for this DHS.

5.5.2 *The TVAB model*

The calculation sheet model developed and used by TvAB (2017), the TvAB model, is used for the DHS assessments in Paper III. In the TvAB model, heat demand over the year is defined for 365 time periods, each representing a day and night, and each time period is calculated separately. Production, fuel use and costs and revenues from production are possible outputs from the TvAB model, which has been extensively used by TvAB for budgeting and investment purposes.

The TvAB model is used in Paper III since no economic optimisation of investment or operation is needed. Instead, production and fuel use with different predetermined CHP plant capacities and production strategies are assessed.

5.6 *Investment calculations*

According to Löfgren et al. (2008), net present value (NPV) is often used for evaluating the profitability of investments. The standard NPV rule states that all independent investments with a positive NPV should be implemented in order to maximise a company's value. This is true when investment resources are unlimited. However, if investment resources are limited, it is of interest to maximise the productivity of these limited resources. A relative measurement, showing the benefit per investment, can be of interest in that case (Lorie and Savage, 1955). Some different methods indicating how the net cash flow of the investment relates to the investment cost have been developed. These methods can be used for evaluating and ranking investment alternatives when investment resources are limited. In Paper II, a relative investment measure, here called equivalent annual annuity ratio (EAAR), is used to evaluate and rank investments when investment resources are limited. This method is employed, together with the NPV, by the owner of Linköping DHS and it is used in Paper II when evaluating and ranking the investments. The NPV and EAAR are both cash flow-based investment measures. The EAAR is used in Swedish literature (Bergknut, 1981; Nilsson and Persson, 1998).

Due to uncertainties in future conditions (e.g. on fuel prices and bank interest rates), investment decisions involve risk taking. The real options theory assumes that the irreversibility of an investment and the uncertainty of future prices can increase the value of postponing an investment. However, this is not captured by the standard NPV rule (Wickart and Madlener, 2007). Studies also show that companies do not base their investment decisions on the NPV rule only (Graham and Harvey, 2001; Sundberg and Sjödin, 2003; Brunzell et al., 2013). Risk management can include adjustment of cash flow or adjustment of discount rates. Another option is to apply safety margins to e.g. the EAAR. In Paper II, the

NPV is used to find the most profitable investment and the EAAR (with safety margins) is used to define when an investment is sufficiently profitable.

In Paper II, the MODEST model is used to determine the magnitude of each investment that gives the lowest future system cost. The NPV and EAAR, both after Swedish corporate taxes, are then calculated for each investment using costs and revenues stated in MODEST results as input data. NPV and EAAR are defined as follows:

$$NPV = I_0 + \sum_{t=1}^n \frac{CF_t}{(1+r)^t} \quad (1)$$

$$EAAR = \frac{NPV}{I_0} * \frac{r}{1-(1+r)^{-n}} \quad (2)$$

where I_0 is the initial investment in period zero (negative value), CF_t is the expected change in net cash flow caused by the investment in period t , r is the cost of capital (interest) and n is the lifetime of the investment.

5.7 Effects on studied GHG inventory totals

5.7.1 Assessments of effects on studied GHG inventory totals

Effects of:

- a reporting company's change in purchase of grid-supplied electricity or DH
- a DH company's investments in production and change in CHP production strategy

on a location-based total and market-based total of a corporate GHG inventory and on a territorial total and BASIC total of a city GHG inventory are analysed.

Parameters used for assessing these effects are listed in Table 5. For electricity in the location-based and BASIC totals, the Corporate Standard and City Standard (WRI/C40/ICLEI, 2014; WRI, 2015) state that firstly, regional grid average emissions should be used and secondly, national grid average emissions (Table 2). In this analysis, national grid averages are used, as general results for Swedish and German locations are sought.

The scope 1 emissions of the BASIC total (WRI/C40/ICLEI, 2014) ("emissions from fuel combustion within the region, but not emissions from energy generation supplied to the grid") (see Table 2) are not included in this analysis. Furthermore, a change in purchase of DH may affect the DHS average emissions factor for DH, which is used in the BASIC total (Table 5). It is not known whether a company or city takes this into account, but in the present analysis the average emissions factor for DH before and after the change in purchases of DH is

considered when assessing the effect on the BASIC total (Table 5). The European national electricity systems are connected to each other and production is co-optimised (see section 2.2). In order to simplify the assessments on effects on the BASIC total, it is therefore assumed that a change in purchase of electricity does not specifically affect the national grid average emissions factor for electricity produced in Sweden or Germany (Table 5).

5.7.2 Assessment of grid average emissions factors

Grid average emissions factors for electricity produced within Sweden and Germany are assessed in Paper III, based on national statistics. For further information, see Paper III.

Average emissions factors of DH are assessed in accordance with the Corporate Standard (WRI/WBCSD, 2006; WRI, 2015). Average emissions factors of DH include emissions from CHP plants allocated to DH and all emissions from HOBs. Emissions from CHP plants are allocated between electricity and heat using the benefit-sharing method (BSM), which is one of the most common allocation methods for CHP production (WRI/WBCSD, 2006).

In the BSM, emissions are allocated proportionally to the energy otherwise needed for separate production of electricity and heat. The share of emissions allocated to electricity $a_{e,i}$ and the share allocated to heat $a_{h,i}$ for fuel i are calculated as (WRI/WBCSD, 2006; EPD, 2015):

$$a_{e,i} = \frac{\frac{E_{e,CHP}}{\eta_{ref\ e,i}}}{\frac{E_{h,CHP}}{\eta_{ref\ h,i}} + \frac{E_{e,CHP}}{\eta_{ref\ e,i}}} \quad (3)$$

$$a_{h,i} = \frac{\frac{E_{h,CHP}}{\eta_{ref\ h,i}}}{\frac{E_{h,CHP}}{\eta_{ref\ h,i}} + \frac{E_{e,CHP}}{\eta_{ref\ e,i}}} \quad (4)$$

where $E_{e,CHP}$ is electricity production in the CHP plant, $E_{h,CHP}$ is heat production in the CHP plant, $\eta_{ref\ e,i}$ is the efficiency reference value for separate production of electricity with fuel i and $\eta_{ref\ h,i}$ is the efficiency reference value for separate production of heat with fuel i .

Table 5. Parameters used in the thesis for assessing effects on studied greenhouse gas (GHG) inventory totals of changes in purchase or production of electricity (E) and district heating (DH). CHP = combined heat and power, DHS = DH system, RE-GO = renewable guarantee of origin

Change in purchases of electricity or DH:			
Quantity	Emissions factor (EF)	The DH company invests in production units or changes CHP production strategy:	
		Quantity	Emissions factor (EF)
Location-based total	E: The reporting company's change in electricity purchase	--	--
	DH: The reporting company's change in DH purchase	Purchases of reporting companies (10% of sales)	Change in DHS average EF for DH
Market-based total	E: The reporting company's change in electricity purchase	--	--
	DH: The reporting company's change in DH purchase	Purchases of reporting companies (10% of sales)	Change in DHS average EF for DH
BASIC total	E: Total change in electricity purchase within the city boundary	--	--
	DH: Taking into account that a change in DH purchase may also affect average EF for the remaining total DH purchases within the city boundary, the effect is assessed as follows: $E_{hp,before} * f_{ha,before} - E_{hp,after} * f_{ha,after}$	Total purchases of DH within the city boundary	Change in DHS average EF for DH
Territorial total	E and DH: Change in emissions from production of electricity and DH within the city boundary caused by a customer's change in purchase of DH.	Change in emissions from production of electricity and DH within the city boundary caused by actions of a DH company.	

* E_{hp} = total DH purchase within the city boundary, f_{ha} = average EF for DH, 'before' refers to 'before change in DH purchase' and 'after' refers to 'after change in DH purchase'.

5.8 Consequential analysis

The following method is used in Papers I-III and in the thesis for assessing consequential changes in global CO₂ emissions occurring when use or production of electricity and DH changes.

When production of DH and electricity in a DHS changes as a result of changed purchase of DH, investment in a DH production plant or a change in CHP production strategy, production in each type of plant before and after the change is first assessed. Changes in global CO₂ emissions are then assessed as the sum of the change in emissions from the DHS and the change in emissions from affected electricity production elsewhere. For the latter, marginal emissions factors for electricity are used (in compliance with recommendations of Azapagic and Clift (1999) and Ekvall et al. (2016), see section 5.2.1). By including changes in emissions from affected electricity production elsewhere, this assessment involves ‘substitution’, a method used in consequential LCA to handle multi-functionalities such as co-production (Pelletier et al., 2015; Brander, 2016). Here, the electricity system is an affected system and the net effect of ‘substituting’ CO₂-rich electricity production elsewhere with CO₂-leaner electricity from the CHP plant is taken into account. When bio-fuel is used in a HOB or CHP plant, the bio-fuel system is also an affected system. However, the effects of increased or decreased use of bio-fuel are not included in the analysis in this thesis (see section 1.2).

Altogether, total changes in global CO₂ emissions (ΔGHG_{global}) due to changes in purchases of electricity or DH, investments in a DH production plant and changes in production strategy can be summarised as follows:

$$\Delta GHG_{global} = \Delta GHG_{local} + \Delta GHG_{affected\ production\ elsewhere} \quad (5)$$

where the net effect on local GHG emissions (ΔGHG_{local}) and the net effect on GHG emissions from affected production elsewhere ($\Delta GHG_{affected\ production}$) are defined as:

$$\Delta GHG_{local} = \sum_{i=1}^n \Delta F_i * f_i \quad (6)$$

$$\Delta GHG_{affected\ production\ elsewhere} = (\Delta E_{e,use} - \Delta E_{e,CHP}) * f_{em} \quad (7)$$

where ΔF_i is the change in use of a specific fuel i for production of heat and electricity at the local DHS, f_i is the fuel emissions factor for that specific fuel, $\Delta E_{e,use}$ is the change in electricity use, $\Delta E_{e,CHP}$ is the change in electricity production in the CHP plants in the DHS and f_{em} represents the marginal emissions factors of the affected electricity production elsewhere in the electricity system.

(Equations 5, 6 and 7 are used in Papers I-III, but with some differences in terminology. For example, in Paper I $\Delta GHG_{affected\ production\ elsewhere}$ is called ΔGHG_{global} . In Paper II and in the thesis, it is the sum of change in local emissions and change in emissions from affected production elsewhere which is called ΔGHG_{global} . In Paper III, the sum of change in local emissions and change in emissions from affected production elsewhere is instead called ΔGHG_{total} . Regardless of these differences in terminology, the equations are the same.)

5.9 Input data

5.9.1 Economics (Paper II)

Investment costs etc. listed in Table 6 are used as input data when optimising investments in Paper II. Operation and maintenance costs for existing and new boilers are included in the MODEST optimisation (see section 5.5.1), since the owner of Linköping DHS questioned the value of continuing to operate the existing coal-fuelled and oil-fuelled boilers, with their high costs for operation and maintenance. Bio-fuelled boilers are assumed to be equipped with FGC and the power-to-heat ratio for B1 is assumed to be 0.5 (TvAB, 2009; Paper II).

Total available heat production capacity for peak and reserve purposes is important in Paper II. Therefore an investment cost is assumed for an eventual additional oil-fuelled HOB that could make the scenarios equivalent in terms of total available heat production capacity. The investment cost for oil-fuelled HOBs is assumed to be € 100 000/MW_{heat}. A nominal bank interest rate of 6% is used for optimisations and the lifetime of all optional investments is assumed to be 20 years. Furthermore, optimisations are made for a 20-year period. The prices for fuels, economic policy instruments and electricity (Table 7, Figure 9) were forecast by TvAB working groups (TvAB, 2009; Paper II).

Table 6. Assumed costs for existing coal-fuelled and oil-fuelled boilers and costs for investment scenarios in Paper II (TvAB, 2009; Paper II)

	Existing coal-fuelled boiler	Existing oil- fuelled boiler	Scenario B1	Scenario B2
Investment costs [k€/MW _{steam}]			950	40
Operation and maintenance [k€/MW _{steam} and year]			20.9	29.9
[k€/MWh _{steam}]	16.2	11.7	1.9	2.2

Table 7. Assumed fuel prices and prices for economic policy instruments for the year 2013 used in Paper II. Annual real increases are assumed to be 0-2.5%. EUAs (European emissions allowances) and electricity certificates are further described in Paper II (TvAB, 2009; Paper II)

	Paper II
<i>Fuel prices [€/MWh]</i>	
Fuel oil	35
Coal	12
Bio-fuel	16-27
<i>Economic policy instruments</i>	
EUAs for fossil fuels [€/EUA]	20
Fuel tax on coal for CHP heat [€/tonne fuel]	17.6
Fuel tax on oil for CHP heat [€/m ² fuel]	20.2
Electricity certificates	-30

Figure 9. Assumed electricity spot prices, except for one assumed peak day per year, used in Paper II. Annual real increase is assumed to be 1.5% (TvAB, 2009; Paper II).

5.9.2 Emissions factors and efficiency reference values

Assumed fuel emissions factors and marginal emissions factors used in Papers I-III and in this thesis are shown in Table 8. Emissions factors used in Paper I in general include upstream emissions (production and distribution of fuels), but not emissions factors used in Paper II (Table 8). In accordance with the Corporate Standard and City Standard, upstream emissions of fuels are not included in the GHG inventory totals analysed in Paper III or this thesis (Table 8). However, upstream emissions of fuels are included in the consequential analysis performed in Paper III and in this thesis (Table 8). The harmonised efficiency reference values in Table 9 are used for allocating emissions from a CHP plant between electricity and heat when assessing average emissions factors of DH (see section 5.7.2).

Table 8. Assumed fuel emissions factors and marginal emissions factor for electricity used in Papers I-III and this thesis (Uppenberg et al., 2001; Sjödin, 2003; Nohlgren et al., 2014; Naturvårdsverket, 2017; Paper I; Paper II; Paper III). GHG = greenhouse gas, NGCC = natural gas combined-cycle

	Cradle-to-gate emissions (Paper I)	Direct emissions (Paper II)	Direct emissions (Used for assessing effects of GHG inventories in Paper III and in this thesis)	Cradle-to-gate emissions (Used for consequential analyses in Paper III and in this thesis)
<i>Fuel emissions factors [kg CO₂/MWh_{fuel}]</i>				
Bio-fuel	0*	0*	0*	7
Light heating oil			267	286
Heavy fuel oil	300	274		
Coal	340	327	335	
Waste	90		(Used in the thesis: 90)	
Natural gas		204	205	205
<i>Marginal emissions factors of electricity [kg CO₂/MWh_{electricity}] (electrical efficiency)</i>				
Coal power plant	1 000 (33%)	728 (46%)		728 (46%)
NGCC plant	370 (58%)	353 (58%)		353 (58%)

*It is assumed that the CO₂ emitted during combustion is absorbed through reforestation and that the biofuel supply is unlimited.

Table 9. Assumed harmonised efficiency reference values used in Paper III and this thesis (EC, 2015; Paper III)

	Harmonised efficiency reference values* (Paper III)	
	Electricity	Hot water
Bio-fuel	0.30	0.80
Oil	0.442	0.85
Coal	0.442	0.88
Waste	0.25	0.80
Natural gas	0.53	0.92

*Separate production of electricity and hot water, construction year 2016, based on net calorific values.

6 Results and analysis

In sections 6.3-6.5, the results in relation to research questions 1-3 (see Chapter 1) are presented. The impacts on average emissions factors presented in section 6.2 are intermediate values, which are used in the analysis and discussion of results relating to the research questions.

Some of the results from Papers I-III are included in this chapter, together with new results obtained in additional analyses performed for this thesis. (Table 3 gives an overview of the source of results for each scenario.)

6.1 Incentivised actors

Incentives in the Corporate Standard and the City Standard are directly targeted at the reporting company and the reporting city, respectively. The reporting company might seek to improve its GHG inventory by changing how much energy it purchases or by changing which energy carrier it purchases (Tables 2 and 5). The reporting city might seek to improve the BASIC total of its GHG inventory by influencing how much energy is purchased within the city or which energy carrier is purchased (Tables 2 and 5). The reporting city might also seek to improve its territorial total by influencing emissions from the production of electricity and DH within the city (Tables 2 and 5). The reporting company and city are therefore directly incentivised by how the Corporate Standard and City Standard value different energy carriers with regard to CO₂ emissions.

The CO₂ emissions associated with electricity and DH are also important for energy companies supplying electricity and DH, as these emissions could affect sales. How the Corporate Standard and City Standard value different energy carriers with regard to CO₂ emissions can therefore indirectly give incentives to energy companies to take actions that reduce the CO₂ emissions associated with the energy carrier they produce.

6.2 Average emissions factors for electricity and DH

In this section, some intermediate results used in the analysis and discussion of the results relating to the research questions are presented.

For purchases of electricity and DH, the Corporate Standard and City Standard are based mainly on average emissions factors (Table 2). However, contractual emissions factors are used in a market-based total. The average emissions factor for electricity produced within Sweden is low (7 kg CO₂/MWh_{electricity}) (Figure 10), due to a large share of nuclear and hydro power (Paper III). The considerably higher average emissions factor for electricity produced within Germany (443 CO₂/MWh_{electricity}) (Figure 10) is a consequence of a high share of coal power (Paper III).

Average emissions factors for DH vary between different DHSs, since production differs. Here, average emissions factors of three DHSs are assessed, before and after acts of a DH purchasing company and of a DH company (Figure 10). Measures that only change purchases of electricity, and not purchases of DH, do not affect the average emissions factor for DH (A2, C1_{bio} and C1_{gas} in Figure 10). As described in section 5.7.2, the average emissions factor for DH includes the emissions from CHP plants that are allocated to heat production (using the BSM as described in section 5.7.2) and all emissions from HOBs. The average emissions factors of electricity and DH presented in Figure 10 are used in subsequent sections in this chapter in relation to answering the research questions.

According to Figure 10, a 10 GWh decrease in DH sales affects the average emissions factor for Linköping DHS (A1 compared with A0) less than for the other DHSs studied (C2_{bio} and C3_{bio} compared with C0_{bio}, C2_{gas} and C3_{gas} compared with C0_{gas}). This is partly due to the BSM effect (section 6.2.1) lowering the average emissions factor for CHP heat compared with HOB heat (further described below). In Linköping DHS, a 10 GWh decrease in DH sales means that DH production is largely reduced in the fossil-fuelled CHP plant. In the bio-fuelled and natural gas-fuelled DHSs, production in the fossil-fuelled HOBs is more strongly affected. Furthermore, as Linköping DHS is larger than the other DHSs, a 10 GWh reduction in DH sales is a smaller share of Linköping DHS. Altogether, this leads to the average emissions factor for the remaining purchases of DH from Linköping DHS (Figure 10) being less affected than for the other DHSs studied.

Figure 10. Average emissions factors (EF) for district heating (DH) and average and contractual EF for heat from electricity (Paper III). For an explanation of scenarios, see section 5.3

6.2.1 *The BSM effect*

In the DHS based on a natural gas-fuelled CHP plant (where natural gas-fuelled HOBs serve as DH peak and reserve production) the average emissions factor for DH is better (lower) when CHP electricity production is utilised ($C0_{\text{gas}}$) compared with when CHP electricity production is refrained from ($C4_{\text{gas}}$) (Figure 10). This occurs because of the BSM effect. According to the BSM (see section 5.7.2), emissions from a CHP plant are allocated between the electricity and DH produced in proportion to the emissions from conventional production of electricity and DH with the same fuel. Therefore, less emissions from the CHP plant are allocated to DH than if the DH had been produced in a HOB with the same fuel. Thus, an advantage is given to the emissions factor for heat from a fossil-fuelled CHP plant compared with heat from a HOB using the same fuel. However, the BSM effect does not occur for CHP production when a ‘zero emissions’ fuel is used, since there are no emissions that can be allocated. This means that no advantage is given to the emissions factor for heat from a bio-fuelled CHP plant compared with heat from a bio-fuelled HOB (assuming that bio-fuel has ‘zero emissions’).

6.2.2 *Allocation of emissions from the HOB*

In contrast to the result for the natural gas-fuelled DHS, the average emissions factor for DH improves (decreases) when electricity production is refrained from ($C4_{\text{bio}}$ and $C5_{\text{bio}}$ compared to $C0_{\text{bio}}$ in Figure 10) in the DHS based on a bio-fuelled CHP plant (where oil-fuelled HOBs serve as DH peak and reserve production). This decrease occurs since HOB heat production decreases when CHP electricity production is refrained from and since all emissions from the oil-fuelled HOBs are attributed to heat production, in accordance with WRI (2015) recommendations on assessments of grid average emissions factors.

6.3 Incentives regarding purchases of electricity and DH

This section presents results relating to research question 1, which asks (section 1.1):

1. *How are measures affecting purchases of electricity and CHP-based DH incentivised by corporate and city GHG inventories and what is the impact on global CO₂ emissions?*

Figure 11 shows how GHG inventory totals of a reporting company and a reporting city in a Swedish location are affected when measures that change purchases of electricity and DH are implemented. Figure 12 shows corresponding results for a German location. (All scenarios in Table 4 and all three DHSs studied are used in the Swedish location and in the German location). Only changes in the location-based and BASIC totals (Table 2) differ between the Swedish location and the German location (Figures 11 and 12), as these totals include average emissions factors for electricity produced within Sweden and Germany, respectively.

6.3.1 Change in purchase of electricity

The market-based total (described in Table 2) would incentivise a reporting company, in both the Swedish and German locations, to purchase contractual emissions factors (section 2.3) for its use of electricity ($C1_{\text{bio}}$ and $C1_{\text{gas}}$ in Figures 11 and 12), as that is an inexpensive way to lower the market-based total (Paper III). However, according to Brander et al. (2018), purchases of contractual emissions factors are not likely to lower global CO₂ emissions. (It is not likely to induce a corresponding increase in production of renewable electricity). Instead, by purchasing renewable contractual emissions factors with ‘zero emissions’ for electricity, the incentive to lower the use of electricity and the incentive not to increase the use of electricity are lost (Paper III).

Likewise, due to the low average emissions factor for electricity produced within Sweden (Figure 10), the location-based, territorial and BASIC totals provide a rather small incentive to decrease purchase of electricity for the Swedish location ($C1_{\text{bio}}$ and $C1_{\text{gas}}$ in Figure 11). This also means that they provide a rather small incentive against increasing purchase of electricity for the Swedish location. In the consequential analysis, on the other hand, a change in the use of electricity has a considerably larger impact on global emissions than shown by any of the GHG inventory totals studied for these cases ($C1_{\text{bio}}$ and $C1_{\text{gas}}$ in Figure 11). This contradiction occurs since the GHG inventory totals do not include changes in emissions from affected electricity production elsewhere.

For the German location, the location-based and BASIC totals give similar incentives to the consequential analysis (changes in global emissions) ($C1_{\text{bio}}$ and $C1_{\text{gas}}$ in Figure 12), as the average emissions factor for electricity produced within Germany is high.

Figure 11. Swedish location. Annual effects on corporate greenhouse gas (GHG) inventories (location-based and market-based totals), city GHG inventories (territorial and BASIC totals) and global CO₂ emissions of actions by companies purchasing electricity and district heating (DH) compared with reference scenarios A0, C0_{bio} and C0_{gas}, respectively. Results opposite to those shown for C1_{bio} - C3_{bio} and C1_{gas} - C3_{gas} apply for actions opposite to these actions (Paper I; Paper III). NGCC = natural gas combined-cycle.

6.3.2 Change in purchase of DH

In Figures 11 and 12, when the change in energy purchases only includes a change in purchase of DH (A1), the territorial total (emissions within the city boundary) is reduced more than the global emissions. This is due to the exclusion of emissions from affected electricity production elsewhere in the territorial totals. The reduced purchase of DH from a CHP-based DHS lowers local production of DH and electricity and local CO₂ emissions, which is shown in the territorial total. However, it can also entail an increase in more CO₂-rich electricity production elsewhere, which is included in the effect demonstrated on global emissions.

Figure 12. German location. Annual effects on corporate greenhouse gas (GHG) inventories (location-based and market-based totals), city GHG inventories (territorial and BASIC totals) and global CO₂ emissions of actions by companies purchasing electricity and district heating (DH) compared with the reference scenario A0, C0_{bio} and C0_{gas}, respectively. Results opposite to those shown for C1_{bio}-C3_{bio} and C1_{gas}-C3_{gas} apply for actions opposite to these actions (Paper I; Paper III). NGCC = natural gas combined-cycle.

6.3.3 Replacing electricity with DH or vice versa

For the Swedish location (Figure 11), the GHG inventory totals studied are affected considerably more by changes in purchases of DH (A1) than changes in purchases of electricity (C1_{bio} and C1_{gas}). This is because the average emissions factor for electricity produced within Sweden is substantially lower than the average emissions factor for any of the DHSs studied (Figure 10). (As with the market-based total, this is due to the ‘zero emissions’ interpretation of the electricity contractual emissions factor.) This also means that it is the change in purchase of CHP-based DH which has the greatest impact on the GHG

inventory totals studied when a purchase of DH replaces a larger purchase of electricity (A2 in Figure 11), and when a purchase of 10 GWh electricity replaces 10 GWh DH (C2_{bio} and C2_{gas} in Figure 11). The low effect of changes in electricity purchases on GHG inventory totals is also the reason for the very small differences in effects on GHG inventory totals when 10 GWh electricity replace 10 GWh DH (C2_{bio} and C2_{gas}) compared with when 2.5 GWh electricity replace 10 GWh DH (C3_{bio} and C3_{gas}).

Thus, in Sweden the Corporate Standard and the City Standard essentially incentivise the reporting company and the reporting city, respectively, to lower purchase of CHP-based DH rather than to lower purchase of electricity. However, the consequential analysis shows that for the implemented measures where DH replaces electricity (A2) and electricity replaces CHP-based DH (C2_{bio}, C3_{bio}, C2_{gas} and C3_{gas}), global emissions can change in the opposite way to the change in the GHG inventory totals for the Swedish location (Figure 11). This contradiction occurs since none of the GHG inventory totals studied includes emissions from affected electricity production elsewhere, which is included in the consequential analysis (Table 5 and section 5.8).

When there are larger changes in purchases of electricity (A2, C1_{bio}, C1_{gas}, C2_{bio}, C2_{gas}), changes in the location-based and BASIC totals are closer to changes in global emissions for the German location (Figure 12) compared with the Swedish location (Figure 11). This is because the average emissions factor for electricity produced within Germany (Figure 10) is closer to the marginal emissions factor for electricity (Table 8). Therefore changes in the location-based and BASIC totals for the German location (Figure 12) correlate more strongly to changes in global emissions than changes in those for the Swedish location (Figure 11) for these measures (A2, C1_{bio}, C1_{gas}, C2_{bio}, C2_{gas}). However, changes in the market-based total and territorial total are similar in the German location (Figure 12) and the Swedish location (Figure 10), as these totals do not include the average emissions factor for electricity produced within the respective country.

6.4 Incentives for a DH company

This section presents results relating to research question 2 (section 1.1), which asks:

2. *How are production strategies in CHP-based DH systems incentivised by corporate and city GHG inventories and what is the impact on global CO₂ emissions?*

Here the incentives in the location-based, market-based, territorial and BASIC totals to a DH company are analysed for two types of production strategies: investments in production plants and changes in CHP production strategy. Integrated parameters that can be affected by a DH company are average emissions factor for DH (Figure 10, Tables 2 and 5) and emissions within the city boundary (Tables 2 and 5).

6.4.1 Investments in new DH production plants

In this section, the profitability of investments is first analysed. This is followed by an analysis of the incentives in the GHG inventory totals studied and the impact on global CO₂ emissions for investments in new DH production plants.

What defines a sufficiently profitable investment?

Paper II studies the effect of unlimited or limited investment resources on investment profitability, combined with an assessment of the impact of investments on local and global CO₂ emissions. Two investment alternatives from Paper II are included in the thesis, a new bio-fuelled CHP plant (B1) and a new bio-fuelled HOB (B2) (Table 4).

According to the MODEST optimisation (see section 5.5.1), the capacity of the optimal CHP plant (with lowest future system costs, section 5.5.1) is relatively high (99 MW_{steam}). This investment has a NPV of 45 M€ and an EAAR (section 5.6) of 4.2%. The optimal HOB has a considerably smaller capacity (24 MW_{steam}). However, when the effects of Swedish corporate taxes are added, its NPV drops to -0.5 M€, whereby the EAAR becomes -0.3%. Thus, the HOB is not a sufficiently profitable investment according to the NPV rule.

According to the NPV rule, the 99 MW CHP plant is a profitable investment. However, assessing profitability based on NPV only implicitly assumes unlimited investment resources, which in reality is rare. In Paper II, investments with long implementation time, and which are based on uncertain future prices of fuel and electricity, are assumed to need an EAAR of at least 6-8% to be sufficiently profitable (Paper II). Assuming limited investment resources and applying this safety margin, the CHP plant is not a sufficiently profitable investment. It is thus less likely that either the CHP plant or the HOB would be implemented if the investment decision were based on economics only (NPV and EAAR). However, investments can also be

made for other reasons, e.g. to meet emissions requirements from customers or city authorities.

Incentives in a GHG inventory and impact on global CO₂ emissions

As stated earlier in this section, the capacity of the economically most optimal HOB (B2) is considerably smaller than the capacity of the economically most optimal CHP plant (B1). Both investment alternatives (B1 and B2) would improve the average emissions factor for DH in the DHS studied (Figure 10) and the GHG inventory totals studied (Figure 13), and would contribute to lowering global emissions (Figure 13). However, on comparing the changes in territorial total (emissions within the city boundary) with the changes in global emissions, the results show that the CHP investment (B1) would lower global emissions more than it would lower the territorial total (Figure 13), since the investment would increase CHP electricity production in the DHS. In contrast, global emissions would decrease less than the territorial total if the HOB (B2) were implemented (Figure 13), as it would lower electricity production in the existing partly fossil-fuelled CHP plant. When investment resources are limited and the highest productivity per investment is sought, these differences can be important. Here, the HOB (B2) provides a greater reduction in the territorial total per Euro invested compared with the CHP investment (B1) (Table 10). Whether the HOB (B2) or the CHP (B1) gives the highest reduction in global emissions per investment depends on which marginal electricity production is assumed to be affected (Table 10).

Table 10. Reduction in CO₂ emissions per Euro invested achieved in investment scenarios B1 and B2 (see Table 4 for explanation of scenarios). CHP = combined heat and power, HOB = heat-only boiler, NGCC = natural gas combined-cycle

	Territorial total	Global emissions, coal power affected	Global emissions, NGCC affected
Investment	[kg CO₂/€]	[kg CO₂/€]	[kg CO₂/€]
B1 (bio-fuelled CHP)	1.0	1.4	1.2
B2 (bio-fuelled HOB)	2.1	1.0	1.6

Figure 13. Swedish and German locations. Annual effects on greenhouse gas (GHG) inventory totals studied and global emissions due to investments in production plants (B1 and B2) and changes in production strategy ($C4_{bio}$, $C5_{bio}$ and $C4_{gas}$), compared with reference scenario B0, $C0_{bio}$ and $C0_{gas}$, respectively (Paper II, Paper III). DHS = district heating system, NGCC = natural gas combined-cycle.

6.4.2 CHP production strategy

In this section, incentives in the studied GHG inventory totals for changes in CHP electricity production strategy are analysed.

DH demand should always be met by the DH company. However, depending on whether electricity production is favourable or not, the DH company can often choose to utilise possible CHP electricity production or to refrain from all or part of it. The analysis of how customers corporate GHG inventory and the city GHG inventory contribute to incentivise

CHP electricity production in a CHP-based DHS shows that GHG inventory totals can change in different ways, depending on the DHS in which electricity production is refrained from ($C4_{\text{bio}}$, $C5_{\text{bio}}$ and $C4_{\text{gas}}$ in Figure 13).

Regardless of DHS, the territorial totals improve when CHP electricity production is refrained from ($C4_{\text{bio}}$, $C5_{\text{bio}}$ and $C4_{\text{gas}}$ in Figure 13), as this lowers the emissions within the city boundary. The territorial total improves most in scenario $C4_{\text{gas}}$, partly as this results in the highest reduction in electricity production. At the same time, the consequential analysis shows that global emissions increase when electricity production is refrained from ($C4_{\text{bio}}$, $C5_{\text{bio}}$ and $C4_{\text{gas}}$) (Figure 13) since, unlike the territorial total, global emissions also include the consequential increase in emissions from affected electricity production elsewhere.

In the natural gas-fuelled DHS, the average emissions factor for DH improves (decreases) when CHP electricity production is utilised compared with when no CHP electricity is produced ($C4_{\text{gas}}$ in Figure 10). This occurs because of the BSM effect, which is described in section 0. Therefore, the customers' location-based and market-based totals and the city's BASIC total worsen (increase) if the DH company refrains from CHP electricity production ($C4_{\text{gas}}$ in Figure 13). The indirect incentive in these totals for the DH company to produce CHP electricity complies with the incentive in the consequential analysis, where global emissions increase when electricity production is refrained from ($C4_{\text{gas}}$ in Figure 13).

Since all emissions from the HOB are attributed to DH production (as described in section 6.2.2) and as there is no BSM effect for heat from a bio-fuelled CHP plant when 'zero emissions' is assumed for bio-fuel (as described in section 0), the emissions factor for DH from the bio-fuelled DHS improves when CHP electricity production is refrained from ($C4_{\text{bio}}$ and $C5_{\text{bio}}$ compared with $C0_{\text{bio}}$). This causes the customers' location-based and market-based totals and the city's BASIC total to indirectly incentivise the DH company to refrain from all or part of CHP electricity production in the bio-fuelled DHS ($C4_{\text{bio}}$ and $C5_{\text{bio}}$ in Figure 13). Still, regardless of DHS, the consequential analysis shows that global emissions increase when CHP electricity production is refrained from ($C4_{\text{bio}}$, $C5_{\text{bio}}$ and $C4_{\text{gas}}$ in Figure 13), as this would increase more CO₂-rich electricity production elsewhere.

6.4.3 *Share of income depending on emissions factor*

Paper III shows that the share of the producer's income which is dependent on the emissions factor differs between the products electricity and DH (Figure 14). This occurs since the electricity spot prices are set regardless of emissions factor (see section 2.2). On the other hand (at least in Sweden), DH is sold by the producer, including information on its average emissions.

Figure 14. Share of income for electricity and district heating which is dependent on the emissions factor (Paper III)

6.5 Basing emissions reduction decisions on GHG inventories

This section presents results relating to research question 3 (section 1.1), which asks:

3. *Are there emissions reduction decisions that should not be based on corporate or city GHG inventories?*

Neither the Corporate Standard nor the City Standard includes emissions from affected electricity production elsewhere. Therefore GHG inventories carried out according to these standards do not include all emissions changes that can occur as a result of an action. This thesis identifies a number of actions where the corporate and city GHG inventories can give differing guidance on CO₂ emissions reductions compared with a consequential analysis.

In Sweden, the location-based, territorial and BASIC totals can give information on the direction of the impact on global emissions for measures affecting only the use of electricity ($C1_{bio}$, $C1_{gas}$ in Figure 11). However, the magnitude of the impact on global emissions identified by the GHG inventories can differ greatly from that identified in a consequential analysis ($C1_{bio}$, $C1_{gas}$ in Figure 11).

Furthermore, in both Sweden and Germany, the market-based total encourages purchases of contractual emissions factors which, according to Brander (2013), does not lead to a decrease in CO₂ emissions. Instead, it leads to the removal of any information on how an increase or decrease in the use of electricity affects global emissions ($C1_{bio}$, $C1_{gas}$ in Figures 11 and 12) (Paper III).

For measures that lead to the replacement of CHP-based DH with electricity, or vice versa, the GHG inventories can give opposing guidance to a consequential analysis (see scenarios A2, C2_{bio}, C3_{bio}, C2_{gas} and C3_{gas} in Figures 11 and 12).

Since local emissions and average emissions factors for DH are important input data in corporate and city GHG inventories, a DH company can be indirectly incentivised by the regulations in the Corporate Standard and City Standard when trying to make its DH product more appealing to a reporting company and city, respectively. This thesis shows that a DH company can improve the average emissions factor for its DH by refraining from bio-fuelled CHP electricity production in the case where fossil-fuelled HOB is used for peak heat production (C4_{bio}, C5_{bio} in Figure 10), whereby an increase in global CO₂ emissions occurs (C4_{bio}, C5_{bio} in Figure 13). Furthermore, the consequential analysis shows that the impact of a CHP-based DHS on a territorial total can be a poor indicator of the impact on global emissions when investments in a CHP plant (B1) and a HOB (B2) are considered and compared (Table 10).

The Corporate Standard and City Standard give several examples of when a corporate or city GHG inventory can be used for emissions reduction decisions. The information in the GHG inventories is suggested to be used to identify reduction opportunities, to set, measure and report on GHG target, to build a GHG abatement strategy and to monitor progress on GHG abatement (WRI/WBCSD, 2013: 3, 11; WRI/C40/ICLEI, 2014: 19, 35). However, the results in this thesis show that, if purchase or production of electricity or DH is included in reduction opportunities or strategies or if a GHG target is set or measured so that it can be affected by purchase or production of electricity or DH, then the studied GHG inventory totals can give misleading or even opposing information relative to changes in global CO₂ emissions.

Furthermore, since measures incentivised by a GHG inventory total can bring about an increase in global emissions (as shown above), implementation of measures which are based on an analysis of consequences for global emissions can result in a worsened corporate and city GHG inventory. This makes the corporate and city GHG inventories less suitable for measuring and reporting on global CO₂ targets or for monitoring progress on CO₂ abatement.

7 Discussion

In this chapter, incentives that derive from methods used in the GHG inventory standards are discussed. The impact and importance of the Corporate Standard and City Standard are also discussed and recommendations are made regarding the CO₂ evaluation of energy carriers when the impacts of companies and cities on GHG emissions are reported and communicated.

7.1 Attributional valuation of CHP-based district heating

The Corporate Standard and City Standard are in general attributional (section 5.2.2), as they are based on average data that reflect the actual physical flows to and from a company or city. Consequential changes in emissions from electricity production elsewhere are thereby not included. The CHP process generally contributes to reduced CO₂ emissions, as less fuel is needed for the co-production of electricity and DH in a CHP plant compared with separate conventional production. The emissions reduction arises when CHP production replaces other production of electricity and heat that causes higher emissions. However, when the replaced production is located outside the boundary of an attributional GHG inventory, the emissions reduction benefits of CHP production are not included in the inventory.

However, the suggested allocation method for emissions from a CHP plant, the benefit-sharing method (see section 5.7.2), allocates emissions to electricity and heat proportionally to the amount of fuel otherwise needed for separate production of electricity and DH with the same fuel used in the CHP plant. Certain emissions reduction benefits are thereby shared between the electricity and DH produced at the CHP plant. However, as the emissions reduction benefits are assessed based on the same fuel used in the CHP plant, the BSM often does not consider marginal fuel use for production of electricity and heat. Moreover, it does not correspond to, or replace, the use of a consequential analysis. This becomes even more evident when the fuel used in the CHP plant is considered to have ‘zero emissions’. Then there are no emissions from the CHP plant to allocate with the BSM, so heat from a bio-fuelled CHP plant becomes equated to heat from a bio-fuelled HOB in terms of impact on CO₂ emissions.

Furthermore, in accordance with the recommendations in the Corporate Standard and City Standard for assessment of grid average emissions factors, all emissions from a HOB are

allocated to DH. This is a common method and, as the HOB produces heat only, it may seem to be logical. However, it results in the illogical finding that the average emissions factor for DH can improve when part of the electricity production is refrained from in a DHS based on a bio-fuelled CHP plant where oil-fuelled HOBs are used for peak heat production. Alternatively, when CHP electricity production increases to its full production potential, the induced increase in CO₂ emissions from the oil-fuelled HOBs can be regarded as a result of the increased electricity production. Therefore, it could be argued that electricity is produced with oil, and not with bio-fuel. On the other hand, the HOB is also needed to provide enough heat to satisfy the total DH demand. Therefore this increase in emissions from the oil-fuelled HOB should perhaps be allocated between the energy carriers DH and electricity. In any case, it should be noted that if CHP-based DH is valued by its attributional average emissions factor and all emissions from HOBs are allocated to DH, an incentive is provided to a number of DH companies to not fully use their possible CHP electricity production capacity.

7.2 The importance of emissions factor for an energy company

How important is it for an energy company to improve the average emissions factor for its electricity or DH? As the emissions factors for purchased energy carriers are vital inputs in GHG inventories of companies and cities (WRI, 2015), they could affect purchases of electricity and DH. This gives an indirect incentive to the energy company to improve the emissions factor for produced electricity and DH. However, due to the differences in the electricity and DH markets (as described in section 2.2), the producer incentive regarding emissions factors differs between electricity and DH. As explained earlier, the electricity producer can sell its electricity on the electricity spot market, where the gross electricity price is set regardless of its origin or emissions factor. Contractual emissions factors for renewable electricity are sold on a separate market, at prices which thus far have been in the order of 0.5-2% of Nordic and German gross electricity prices (Paper III). The DH markets work differently, as DH is sold on local markets and (at least in Sweden) the DH company sells DH including information on its average emissions factor. The average emissions factor can then be the key determinant for whether the DH is sold or not (Paper III). Thus, for the producers of energy carriers, the average emissions factor for DH produced can be considerably more important than the average emissions factor for electricity produced (Figure 14).

7.3 Effects of the use of contractual emissions factors

As described earlier, the market-based total of a corporate GHG inventory incentivises companies to purchase contractual emissions factors for electricity, such as RE-GOs, as this is an inexpensive way to claim ‘zero emissions’ for the company’s use of electricity. However, as neither of the two large systems where RE-GOs can be used (corporate GHG inventories, described in section 3.1, and European electricity disclosure, described in section 2.3) entails mandatory demand for electricity RE-GO or requires additionality, it is less likely that a purchase of RE-GOs will induce a corresponding increase in renewable electricity production (Brander et al., 2018; Paper III). There is also a large surplus of electricity RE-GOs in Europe, because of previous investments, government support schemes and investments profitable without support schemes (IEA, 2017). Furthermore, the methods used in the Corporate Standard (and in the City Standard) do not capture the emissions reduction benefits of utilising the excess heat from CHP electricity production. An energy purchasing company thereby gains an improved corporate GHG inventory and seemingly appears to contribute to an emissions reduction if it purchases electricity RE-GOs and uses electricity for heating purposes instead of excess heat from CHP electricity production. The use of electricity RE-GOs thereby counteracts CHP production and its contribution to emissions reduction.

Furthermore, when electricity RE-GOs with ‘zero emissions’ are used, there is no incentive in the market-based total of the corporate GHG inventory to reduce use or purchases of electricity.

7.4 Influence of the Corporate Standard and City Standard

Based on the above, it is important to consider what impact the Corporate Standard and City Standard could have on global CO₂ emissions with regard to the use of electricity and DH. According to WRI/WBCSD (2013), the purchase of electricity, heat and steam “represents a significant reduction opportunity” as it constitutes a “major source of GHG emissions for companies”. Furthermore, in 2015, world emissions from fuels combusted in electricity production plants, CHP plants and HOBs collectively represented about 35% of direct CO₂ emissions from global combustion of coal, oil and natural gas, with electricity production constituting most of this 35% (IEA, 2017).

There is no readily available information about the market share of the City Standard for city GHG inventories. The Corporate Standard, on the other hand, is the most widely used standard for corporate GHG inventories, according to Green (2010) and WRI/WBCSD (2013). It has also influenced many other standards for corporate GHG inventories and is used in many voluntary and compulsory GHG programmes around the world. In addition, the methods of the Corporate Standard have been adopted in the ISO standard for quantification

and reporting of GHG emissions in organisations (ISO14064-1), as described by Green (2010). Furthermore, the widespread Corporate Standard is likely to have influenced regulations concerning GHG emissions reductions (Green, 2010; Andrew and Cortese, 2011).

Altogether, this means that the way in which the Corporate Standard and City Standard value different energy carriers with regard to CO₂ emissions, and what they suggest a corporate or city GHG inventory should be used for, could have a large impact on global CO₂ emissions.

7.5 Recommendation for assessing the impact of companies and cities (regions) on CO₂ emissions

The attributional Corporate Standard and City Standard do not capture the total consequences for global CO₂ emissions of a decision, either for actions that cause changes in use of electricity or for actions that entail changes in CHP production. This thesis shows that an increase, instead of a decrease, in global emissions can therefore be caused when incentives in corporate or city GHG inventories are used for emissions reduction decisions.

The Corporate Standard and City Standard could stop recommending, or even recommend against, use of GHG inventories for decision making. However, when time and effort have been invested in performing a GHG inventory, which has then been reported and communicated, it can still be considered likely that conclusions will be drawn based on the information in that GHG inventory, followed by decisions based on these conclusions. When GHG inventories based on attributional CO₂ emissions and contractual emissions factors are made, reported and communicated, it is within the bounds of probability that actions intended to affect CO₂ emissions will target attributional CO₂ emissions and contractual emissions factors, instead of global CO₂ emissions. What management focuses on and makes sure is measured and communicated is likely to be acted on (Catasús, 2007; Schaltegger and Csutora, 2012). As expressed in the often used adage “what gets measured gets managed”, which is also mentioned by the Corporate Standard (WRI/WBCSD, 2013: 11).

An attributional corporate GHG inventory and an attributional city GHG inventory allocate the responsibility for CO₂ (or CO₂eq) emissions between companies and between cities (WRI/WBCSD, 2013; WRI/C40/ICLEI, 2014). This allocation shows the amount of emissions for which a company or a city is responsible. Moreover, it indicates which company or city can (and ought to?) take measures to lower these emissions. When used for monitoring and reporting on progress on emissions reductions, the GHG inventory also shows how successful a company or a city has been in terms of reducing emissions. This thesis shows that emissions reduction decisions based on consequential analysis, although they can lower global CO₂ emissions, could worsen an attributional corporate or city GHG inventory. In order to be able to report and communicate an improved attributional GHG inventory, the

reporting company or city therefore must base its emissions reduction decisions on average or contractual emissions factors. Thus, if actual reduction of global CO₂ emissions is what is desired, attributional and contractual emissions factors should be avoided for purchases of electricity and DH when assessing, reporting and communicating the impact of companies and cities on GHG emissions. The use of a consequential approach is instead recommended.

One of the arguments against the use of consequential methods is that it can be difficult to determine the consequences with high precision (Tillman, 2000; Ekvall et al., 2005). The British logician Read (1898: 351) once wrote: “It is better to be vaguely right than exactly wrong”. The results in this thesis suggest that it is perhaps better to be ‘vaguely right’, using approximate marginal emissions factors, than ‘exactly wrong’, using more exact average and contractual emissions factors based on local emissions only, when assessing the impact on CO₂ emissions of purchases of electricity and CHP-based DH.

8 Conclusions

This chapter presents some specific conclusions on the research questions (section 8.1) and draws some general conclusions regarding the starting hypothesis (section 8.2).

8.1 Conclusions in relation to the research questions

The following conclusions can be drawn with regard to the research questions.

Research question 1. How are measures affecting purchases of electricity and CHP-based DH incentivised by corporate and city GHG inventories and what is the impact on global CO₂ emissions?

Corporate and city GHG inventories generally use average emissions factors for purchases of electricity and DH, and thus emissions from affected electricity production elsewhere are not included. This thesis reveals that such inventories can show large differences in magnitude of effects on CO₂ emissions for changed purchases of electricity or DH, compared with the effects on global emissions shown in a consequential analysis (A1, C1_{bio} and C1_{gas} in Figure 11). In addition, when electricity replaces DH, or vice versa, the inventories can show opposing effects on CO₂ emissions compared with global emissions (A2, C2_{bio}, C3_{bio}, C2_{gas} and C3_{gas} in Figures 11 and 12). Therefore, when used for CO₂ emissions reduction decisions that affect purchases of electricity or replacement of CHP-based DH with heat from electricity (or vice versa), corporate and city GHG inventories can contribute to an unintended increase in global GHG emissions.

Research question 2. How are production strategies in CHP-based DH systems incentivised by corporate and city GHG inventories and what is the impact on global CO₂ emissions?

In corporate and city GHG inventories, purchased energy carriers, such as electricity and DH, are in general valued by their average emissions factors. A low average emissions factor makes an energy carrier more appealing to a reporting company and city, which may positively affect sales of that energy carrier. Furthermore, emissions from production of

electricity and DH within the city boundary are important for a reporting city focusing on the territorial total. Thus, corporate and city GHG inventories could indirectly incentivise a DH company to lower the average emissions factor for DH and local emissions from its production of electricity and DH.

Regarding investments in DH production plants, this thesis shows that territorial total analysis and consequential analysis value HOB and CHP investments differently (B1 and B2 in Figure 13). Such discrepancies can cause differences in guidance on the investment that will give the greatest reductions per Euro invested. Moreover, for bio-fuelled CHP production, when oil is used for peak heat production, it is shown that the GHG inventory totals studied can be improved when CHP electricity production is lowered, despite an increase in global emissions according to consequential analysis (C4_{bio} and C5_{bio} in Figure 13). The territorial total is improved when CHP electricity production is refrained from also for natural-gas fuelled DHS, although consequential analysis shows an increase in global CO₂ emissions. Thus, the GHG inventories of customers or cities could indirectly incentivise a DH company to adopt production strategies that increase global CO₂ emissions.

Research question 3. Are there emissions reduction decisions that should not be based on corporate or city GHG inventories?

Basing emissions reduction decisions that affect purchases or production of electricity or DH on a corporate or city GHG inventory could lead to an unintended increase in global CO₂ emissions, as neither of these GHG inventories captures the total consequences for global CO₂ emissions.

It can be concluded that decisions which change purchase of electricity or involve replacement of CHP-based DH with heat from electricity (or vice versa) could lead to unintended increases in global CO₂ emissions when based on a GHG inventory total. Such decisions should therefore not be based on how they affect a corporate or city GHG inventory.

Furthermore, it is shown that changes in the territorial total do not necessarily reflect changes in global CO₂ emissions when investments are made in production plants in a CHP-based DHS. It is also shown that the GHG inventory totals studied could be improved by refraining from CHP electricity production, although this increases global CO₂ emissions. Decisions on investments in DH production plants in CHP-based DHSs should therefore not be based upon how they affect the territorial total of a city GHG inventory. Moreover, decisions on CHP electricity production should not be based upon how they affect the average emissions factor for DH, or upon how they affect GHG inventories of customers or of the city where the DH is produced, as that could result in an unintended increase in global CO₂ emissions.

It can also be concluded that CO₂ reduction decisions, such as ‘identifying reduction opportunities, setting GHG targets or building a strategy to manage and reduce GHG emissions’, based on an attributional CO₂ valuation (average emissions factors) of purchased energy carriers, could result in a lower reduction in global CO₂ emissions or even increase global CO₂ emissions. Correspondingly, CO₂ emissions reduction decisions affecting purchases of electricity and DH based on a consequential analysis could worsen a corporate or city GHG inventory. This implies that a GHG inventory can give different or even opposing information when used for measuring and reporting on goals or progress regarding GHG reductions, compared with a consequential analysis. Thus, none of these emissions reduction decisions should be based on a corporate or city GHG inventory if purchase or production of electricity or CHP-based DH could be affected.

8.2 General conclusions

The hypothesis tested in this thesis states that:

The use of corporate and city GHG inventories for CO₂ emissions reduction decisions can counteract reductions in global CO₂ emissions in the case of electricity and CHP-based DH.

Based on the answers to research questions 1-3, as summarised in the sections above, it can be concluded that CO₂ reduction decisions based on either a corporate or a city GHG inventory could counteract reductions in global CO₂ emissions when electricity or CHP-based DH is affected.

9 Further work

When comparing incentives in corporate and city GHG inventory totals with the incentives found in consequential analyses, this thesis deals with emissions from affected electricity production elsewhere, while bio-fuel supply is assumed to be unlimited. The analysis could be expanded by combining effects on emissions from affected electricity production elsewhere with market-mediated effects on emissions due to limited supply of bio-fuel.

Indirect incentives given to a DH company by its customers' corporate GHG inventories and the city GHG inventory of the city or region in which the DHS is located are studied in this thesis, as are the associated effects on global CO₂ emissions. Future studies could analyse incentives in a corporate GHG inventory when a DH company is the reporting company.

Studies are also needed on possible design and consequential analyses of introducing contractual emissions factors for DH that include the emissions reduction benefits of CHP production compared with separate conventional production of electricity and DH, which could be included in a future framework for guarantees of origin for DH.

Based on the results of Paper III and of the additional analyses presented in this thesis, it can be concluded that emissions reduction decisions which affect purchases of electricity or CHP-based DH should not be based on attributional corporate or city GHG inventories. Further studies are needed to develop a method that better captures the changes in global GHG emissions due to changes in purchases of energy carriers. This method could be used by corporations and cities or regions for identifying reduction opportunities, setting GHG targets, building a strategy to manage and reduce GHG emissions, and measuring and monitoring a company's progress in terms of reduced global CO₂ emissions, including measuring and reporting regarding goals on GHG reductions.

Studies on the extent to which attributional analyses (GHG inventories and other analysis) and consequential analyses are actually used by companies, cities and regions in different stages of decision making (such as learning, identifying reduction opportunities and choosing an action among others) are also important, especially regarding the use and purchase of electricity and DH.

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Papers

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