Ristimäki, Miro; Säynäjoki, Antti; Heinonen, Jukka; Junnila, Seppo

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Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design

Miro Ristimäki*, Antti Säynäjoki, Jukka Heinonen, Seppo Junnila

Aalto University, School of Engineering, Department of Real Estate, Planning and Geoinformatics, P.O. Box 15800, 00076 Aalto, Finland

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ABSTRACT

Due to the growing threat of climate change, we are challenged to find improved assessment practises to recognize solutions for sustainable urban development. The focus of the study is on the life cycle design of a district energy system for a new residential development in Finland. This study analyses LCC (life cycle costs) and carbon emissions (LCA (life cycle assessment)), i.e., the "viability" of different energy systems through a methodological life cycle framework. By combining LCC and LCA, a LCM (life cycle management) perspective is portrayed to support decision-making on a long-term basis. The comparable energy design options analysed are (1) district heating (reference design), (2) district heating with building integrated photovoltaic panels, (3) ground source heat pump, and (4) ground source heat pump with building-integrated photovoltaic panels. The results show that the design option with the highest initial investment (4) is in fact the most viable from a life cycle perspective. This study further strengthens the connection between cost savings and carbon emissions reduction in a life cycle context. Thus, by implementing LCC and LCA analysis in an early design phase, justified economic and environmental design decisions can be identified to develop more sustainable urban areas.

1. Introduction

It is often stated that the three dimensions of sustainable development (economic, environmental and equity) tend to contradict each other in urban planning [1,2]. Finding solutions that would support progress in all three of these aspects is thus a big challenge. Godshalk (2004) has further studied the value conflicts within sustainable development between ecology, economy and equity. He has boldly suggested that ecology (i.e., the environment) and economy should be the primary values, and that equity should be seen as a secondary objective in order to enhance urban planning [3]. While opposite opinions exist as well (e.g., in the Nordic countries, the social aspect of urban development is mandated by legislative processes), focussing on these two aspects certainly forges the way in the search for viable sustainable solutions.

The focus in environmental sustainability in urban development has lately been dominated by climate change. The spotlight in research and policy-making is on cities, especially on residential buildings and transportation due to their dominant role in global growth [4,5]. Demographic changes indicate that by the year 2050, 70% of the world's population will live in cities [6]. In terms of emissions and energy consumption, cities produce about 80% of all GHG (greenhouse gas) emissions and consume 75% of energy globally [7]. Simultaneously, the global building stock is responsible for approximately 30–40% of energy use and carbon emissions [8]. In Europe, the major share of these emissions actually derives from heating alone [9].

It seems that residential development could present a grand opportunity to decrease energy demand and reduce carbon emissions cost-effectively with combining existing knowledge and technology [10,11]. The highest economically feasible mitigation potential is suggested to be found in the residential and commercial sector; a possible 29% reduction is insinuated in relation to the projected emission baseline for year 2020 [6].

Public and private acquisitions in present development can be argued to be made predominantly based on short-term investment values and not from a life-cycle driven perspective [12]. This may lead to development potentially conflicting with all the sustainability dimensions.

By employing a life cycle perspective through LCM (life cycle management); LCC (Life cycle costing) and LCA (life cycle assessment) have been introduced to provide information for managing sustainable development. Hence, the life cycle perspective (or life cycle thinking) does not get the required attention [13]. Klöpffer, W.

* Corresponding author. Tel.: +358 44 3624723.
E-mail address: miro.ristimaki@aalto.fi (M. Ristimäki).

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(2008) and Finkbeiner et al. (2010) have introduced a tool for LCSA (life cycle sustainability assessment), which is defined as: LCA + LCC + SLCA (LCA = Environmental Life Cycle Assessment, LCC = Life Cycle Costing, SCLA = Social Life Cycle Assessment) [14,15]. Connecting both environmental and economic aspects would further strengthen the importance of the concept life cycle management in the early design stages of urban development [16].

When combining economic and ecological dimensions, they can be claimed to complement each other in residential development. Lower energy consumption equals lower running costs. When this thinking is extended throughout the life cycle of a new residential development, the savings might be significant compared to the initial investment. According to McKinsey & Company (2009), the built environment sector has an excellent economic potential to reduce GHG emissions by the year 2030 [17]. Accordingly, only the power generation sector has more potential. Energy efficiency as a category has the most abatement opportunities, in which building insulation possesses a significant role [17]. The study suggested that minor design changes in construction have a significant carbon reduction impact with a payback-time close to zero for both carbon emissions and the respective operational costs.

The existing literature presents some examples of combining the economic and ecological dimensions of life cycles. Carlsson Reich (2005) attempted to combine economic LCC with environmental LCA in the case of municipal waste management systems. The environmental effects were monetized in order to introduce a common unit to measure both life cycle costs and environmental effects [18]. The methodology enabled the analysis, but issues of consistent methodology between economic assessments and environmental LCAs remained. Heijungs et al. (2012) introduce a way of calculating economic and ecological life cycle costs in one assessment model [19]. Similarly, Junnila (2007) has presented a combined LCC and LCA framework for life cycle management of energy-consuming products [20]. Lijing Gu et al. (2008) have created a method where LCA and LCC are combined for addressing the life cycle green costs of buildings. LCA of different building design options was analysed and converted into LCC costs for emissions. Afterwards the emission costs derived from LCA were added to the conventional LCC outcome [21]. Brown et al. (2011) have proposed a life cycle management approach for large-scale development resorts, where LCC and LCA are combined in order to create designs that provide environmental benefits with low operational costs [22].

The purpose of this study is to examine whether a residential development can in practice deliver the claimed sustainable viability, i.e., simultaneous environmental and economic benefits. The study combines LCC and LCA in a case of a residential district energy system area in Finland aiming to identify the actual technologies that could provide the highest sustainable viability and assesses the emissions and relative mitigation potentials associated with the different technologies.

Additionally, this study examines whether investments in modern energy systems are feasible in both the economic and ecological perspective. Thus, the LCC and LCA analyses are carried out separately. Combining LCC and LCA brings added value to life cycle management. By enhancing the position of life cycle management, profound sustainable solutions can be identified and implemented.

The study suggests that investments in new technology in heat and electricity production provide savings in costs and GHG emissions. However, the break-even points of the investments occur significantly sooner ecologically than economically.

The structure of this paper is as follows: The research methods are presented in Section 2, followed by a detailed description of the research process in Section 3. The results of the study are presented in Section 4. The implications and uncertainties related to the results are discussed in Section 5. Finally, conclusions of the study are presented in Section 6.

In order to avoid misinterpretation, the terms *life cycle viability* and *life cycle affordability* are defined. Life cycle viability (in urban development) is defined as merging economic and environmental sustainability [23]. Life cycle affordability is defined as a calculated net present value measure (€/m^2/a) representing overall cost-efficiency during a defined time period.

2. Research methods

The research methods applied in this study are life cycle costing (LCC) and environmental life cycle assessment (LCA). It is important to note that the LCC and LCA methods function similarly, although they quantify their outcome with different measures: LCC is for purely economic assessments, whereas LCA is for environmental assessments.

2.1. Life cycle costing (LCC)

LCC is a valuable financial approach for evaluating and comparing different building designs in terms of initial cost increases against operational cost benefits with a long-term perspective. The key incentive for applying an LCC analysis is to increase the possibility of cost reductions for the operational phase, even if an additional increase in the initial investment is necessary [24]. By applying an LCC perspective in the early design phase, decision makers are able to obtain a deeper understanding of costs during the life cycle for different design strategies. Buildings are a long-term investment associated with environmental impacts over a long duration [25,26]. Fundamental environmental responsibility aims for a long-term view and with that an understanding that initial design decisions have a significant impact over a building's life span [25].

LCC is defined as "a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors, both in terms of initial costs and future operational costs" (Standardized Method of Life Cycle Costing for Construction Procurement ISO15686, 2008) [27]. It is important to notice that traditional LCC is purely economical and does not take into account environmental aspects [24]. Earlier development has focused on developing LCC methodology for the construction industry and placing LCC in an environmental context [28]. Sterner E. (2002) developed an LCC model to calculate the total energy costs for buildings [29].

The LCC theory foundation is properly developed by Flanagan et al. (1989) and Kirk & Dell'Isola (1995) along with essential decisions and activities to undertake an LCC analysis [30,31]:

- **Defining alternative strategies to be evaluated** – specifying their functional and technical requirements
- **Identifying relevant economic criteria** – discount rate, analysis period, escalation rates, component replacement frequency and maintenance frequency
- **Obtaining and grouping of significant costs** – in what phases different costs occur and what cost category
- **Performing a risk assessment** – a systematic sensitivity approach to reduce the overall uncertainty

In order to compare different alternatives, a derived indicator consisting of net present cost of all relevant life cycle costs is calculated. The LCC annual equivalent is defined as €/m^2/a (net present cost) for the chosen evaluation period (Standardized Method of Life Cycle Costing for Construction Procurement

ISO15686, 2008, Chapter 5 metrics) [27]. In this study, this indicator represents a life cycle affordability comparator for the different options.

The LCC methodology can (and must) be criticized. A LCC analysis is based on the estimation and valuation of uncertain future events and outcomes; hence, subjective factors are involved in the process and will affect the results [24]. As stated above, the annual energy indexation is an uncertain factor which has an impact on the life cycle outcome.

Even though LCC is not recognized as theoretically accurate, the LCC methodology presents many benefits. For example, the analysis provides an indication of what strategic options and aspects to seriously consider, the results of the LCC analysis are presented with a common unit (currency), an LCC analysis processes and simplifies a huge amount of information and provides a valuable life cycle perspective to the different alternative options [24].

From a user and consumer perspective, it is valuable to link environmental issues with financial outcomes in a strategic decision making context. However, it is important to note that the LCC methodology is developed only for financial analysis, whilst LCA assessment focuses on the environmental impact.

2.2. Life cycle assessment (LCA)

Life cycle assessment (LCA) is an established way of measuring total environmental effects of products and services. LCA takes all the phases of a product life cycle into account, starting from the acquisition of raw materials to the end-of-life phase (e.g., disposal of product or demolition of a building) [32]. The International Standard ISO 14040 defines the phases of an LCA as follows [33]:

- **Goal and scope definition** – defines the goal, characteristics and borders of an LCA.
- **Inventory analysis** – defines the characteristics of data collection and calculation procedures.
- **Impact assessment** – evaluates the potential significance of the results of LCA.
- **Interpretation of results** – the findings of the inventory analysis and the impact assessment are combined together.

The most established methods in LCAs are process LCA and IO-LCA (input–output LCA). The process LCA is a traditional way of analyzing product life cycle emissions. The principle of the process LCA is to calculate GHGs of each process of the product life cycle individually in order to form a chain of the processes that covers the whole life cycle [34]. Each process analysis is conducted using process-specific primary (i.e., material and energy flows in the manufacturing process) and secondary data (i.e., amount of GHG emissions per manufacturing process), which lead into very accurate results of the modelling [34]. However, there is nearly an indefinite amount of single processes in a product life cycle, and including all of them in the modelling is practically impossible. This problematic characteristic of process LCA modelling is known as a truncation problem [35]. A process LCA practitioner has to define a border that separates the processes included in the modelling from those that are left out of it. Thus, it is probable that significant processes are also left out of the modelling along with the insignificant ones [35]. Process LCAs are also very laborious and require a large amount of data since secondary data has to be acquired separately for each process. Furthermore, process LCA software is usually expensive.

Another widely used LCA method, IO LCA, was invented in the 1970s by Nobel Prize winner Wassily Leonthief. IO-LCA converts monetary costs into environmental effects, often according to national input–output matrices. There are a few different IO LCA models for different economies, but also more and more prevalent are the so-called multi-region IO models. The truncation problem is not an issue in IO LCAs since every sector of a national economy is included in a model and the number of included sectorial transactions is indefinite [32,36,37]. Additionally, data requirements are significantly different between IO LCAs and process LCAs. IO LCAs require monetary transaction data, whereas process LCAs requires detailed data on the material and energy flows of all processes in a production process chain [34]. All required secondary data in the IO LCAs lie within the IO LCA matrices, while process LCAs require case-specific secondary data [32,34].

IO LCA suffers from the aggregation problem since even in the most disaggregated models, several industries as well as all the products of a specific industry are aggregated into each IO sector. The industry sectors in IO LCAs thus represent the averages of several sectors of an economy, making the method not applicable in modelling specific products or comparing similar products within one industry [35]. Additionally, IO LCA models in general appear as a "black box" to the LCA practitioner [38]. Thus, examining characteristics of a specific process within an IO LCA model is usually impossible. Partly related to the same issue, two other well-recognized problems of IO LCAs are homogeneity and proportionality assumptions [39]. Of these, the homogeneity assumption means that sector outputs are assumed to be proportional to price, regardless of the variation of products inside a sector [39]. The proportionality assumption means that the inputs to a sector are assumed to be linearly proportional to its output [39].

The study utilizes a recently developed IO model, ENVIMAT, which is based on the IO matrices of the Finnish economy. The study utilizes the producer price version of the ENVIMAT model with a table of 151 industries. The model was generated using the characteristics of 918 Finnish products or services and 722 imported products or services [40]. Seppälä et al. (2009) provide more detailed information on the ENVIMAT model [40].

The hybrid LCA method combines the process LCA and IO LCA into a single model. The method combines the advantages of the two traditional LCAs and avoids known problems. Using hybrid LCA avoids the truncation problem of the process LCA and relieves the issue of the aggregation problem inherent in IO LCA modelling [41]. One of the most popular applications of hybrid LCA is tiered hybrid LCA, which consists of process LCA for the emissions of production processes, whereas the indirect emissions are modelled with IO LCA. As a result, the model is accurate since process data is used for the most important processes (avoiding the aggregation problem) and IO LCA covers the supply chains (avoiding the truncation problem).

3. Research process

3.1. The residential development of Härmälänranta

The residential development of Härmälänranta is located in Tampere, Finland's third largest city by population (approx. 211,000 residents). The development site is situated about 5 km southwest of Tampere city centre and has decent public transport connections. The residential development is divided into two phases, which will be executed during the years 2012–2020. The first phase of the development will be examined in this study; it includes seven multi-story residential buildings (3078 gross m^2 each with 28 apartments), and the area is designed for about 546 residents.

The city of Tampere is one of the fastest growing cities in Finland. Estimations report that by the year 2030, approximately 45,000 new residents will move to the city, which will further increase energy consumption and GHG emissions. In an attempt to manage a sustainable urban development, Tampere is currently pursuing a program (named ECO_2) where the objective is to achieve a 20% GHG emission decrease by 2020, which is an even greater decrease than European Union requirements. A longer term objective is to produce 80% of energy production with renewable energy sources by 2040. The residential development of Härmälänranta is therefore a significant development for the city regarding these energy efficiency objectives [42].

3.2. Energy systems of the case area

The seven buildings of the residential development have six stories with one elevator and a single staircase. A heat recovery system is installed along with water circulation to heat the sanitary areas. The development of 21,546 m^2 consumes 93.60 kWh/m^2, including heating, domestic hot water and communal electricity for appliances, air-conditioning fans and lighting in the buildings. Household electricity used by residents is not included in this study.

The study considers three different energy systems for the Härmälänranta residential area along with combinations of some systems. The following list briefly introduces each of the three.

- District heating:
  - o According to Pöyry Management (2011) [43], district heating (i.e., the joint production of electricity and heat) has a significant role in providing heat for Finnish buildings, especially in urban areas. Accordingly, more than 90% of residents live in district-heated buildings in the major cities in Finland. The advantages of district heating lie in a good coefficient of efficiency and low production-phase emissions due to larger scale production compared to decentralized heating systems using fossil fuels. However, district heat production relies rather heavily on fossil fuels, which results in higher fuel costs and more GHG emissions compared to renewable energy technologies [44].
- Ground source heat pump:
  - o Geothermal Heat Pumps combine a heat pump with a ground heat exchanger [45]. A ground source heat pump produces more energy than it requires for operation, thus resulting in energy savings measured by a performance coefficient [45]. Ground source heat pumps have a performance coefficient of approximately three [46], which mean that the system provides three times more energy than it uses for operation.
- Building integrated photovoltaic panels:
  - o According to the Florida Solar Energy Center (2007) [47], photovoltaics are semiconductor devices that are used to convert sunlight into direct current electricity. They are often called solar cells. The advantage of photovoltaic panels is that fuel (i.e., sunlight) is free and energy generation with photovoltaic panels causes no noise or pollution. However, the high cost and resource needs of photovoltaic equipment are currently the primary limiting factor for the technology. The photovoltaic panels used in this study are designed as stand-alone panels integrated in the buildings through roof installment (building-integrated). The panels are calculated to generate 10% of the overall energy demand of the buildings. The calculations are performed according to the National Building Code of Finland. The proposed photovoltaic panels are calculated to generate 897 kWh/m^2 (according to the location of the development) and have a system efficiency of 8.7%. In order to provide 10% of the building's energy demand, a total of 2575 m^2 photovoltaic panels are to be installed on the buildings' roofs to provide electricity for appliances, air-conditioning fans, and lighting in the buildings.

3.3. Defining energy options to be evaluated

The energy options to be evaluated are the base case scenario along with alternative options, where different energy systems are combined. The four different options are:

1. **District heating (the base case scenario)**: District heating, since there is an existing infrastructure in the area to be utilized. The electricity for the building is received from the local supplier.
2. **District heating with building integrated photovoltaic panels**: District heating (for heating) combined with building integrated photovoltaic panels that will generate 10% of the overall energy demand allocated to electricity for appliances, air-conditioning fans and lighting in the buildings.
3. **Ground source heat pump**: Ground source heat pump system to produce the heating of the building (operating electricity bought from a local energy supplier). The electricity for the building is received from the local supplier.
4. **Ground source heat pump with building-integrated photovoltaic panels**: Ground source heat pump system to produce the heating for the building (operating electricity bought from a

Table 1
Origin of data.

Data category	Origin of data
Investment cost data	Investment cost data concerning construction and infrastructure (including district heating and ground source heat pump options) of the residential area is attained from cost estimators representing the construction company. Costs representing the photovoltaic panels are acquired from a local supplier.
Energy demand data	IDA ICE (IDA Indoor Climate and Energy) building simulation performed by the building services project manager of the construction company
Local energy costs	Local energy company for district heating and electricity.
Renewable energy	Characteristics (including cost/panel (m^2), production capacity and life cycle replacement schedule) of the building integrated photovoltaic panels were obtained from a local supplier.
Maintenance costs	Design manager of the construction company provided an estimate of the maintenance costs. Additionally, maintenance costs for the facilities were obtained by performing a building maintenance cost plan (including operational costs) of the buildings [48].
Other life cycle costs	Design manager of the construction company provided an estimate (year of replacement and costs) of life cycle works for the energy systems. Additionally a life cycle repair and replacement schedule for the building elements was established in accordance with a reference guide (costs are indexed to present value (2012)). [49]
Economic parameters	In order to estimate net present costs of the different design options, indexation and discount rates were chosen to reflect a stable macro-economic situation. The chosen values are justified in the process description chapter.

local energy supplier) combined with building-integrated photovoltaic panels which will generate 10% of the overall energy demand allocated to electricity for appliances, air-conditioning fans and lighting in the buildings.

3.4. Acquiring case data

The quantitative cost data for the LCC and LCA analysis was acquired through co-operation with the construction company (including suppliers) in charge for the residential development. In the data table (Table 1) below, the origin of the data is presented.

The LCC analysis employed all the acquired cost data (Table 1) during the life cycle. By applying the economic criteria, the current net cost could be attained. The LCA analysis of the study utilizes construction costs of buildings, infrastructure and energy systems plus energy consumption amounts as initial data for the assessment of construction phase emissions. Costs of maintenance, repair and replacement plus amounts of energy consumed in the operation phase of the building were used as initial data in the use-phase assessment. In order to make a comprehensive assessment, different time perspectives were used in the life cycle analysis. The chosen time periods were 25, 50 and 100 years.

3.5. Process description

The LCC and LCA analyses of the study were first carried out separately, and the results of the analyses were then combined for cross-examination. Accordingly, the conclusions of the study are primarily based on the cross-examination of the results. However, in order to allow an in-depth view of the research design and results, both LCC and LCA analyses are presented in detail in the following sections.

3.5.1. LCC

The life cycle costing is divided into a construction and a use-phase assessment. In the construction part, the initial investment costs are attained. In the use-phase assessment, energy consumption, operational costs, maintenance costs and building-related replacement schedules are estimated. Additionally, relevant economic criteria for LCC are defined.

3.5.1.1. Construction phase assessment. The first step is to acquire relevant cost data for the evaluation of the different options [30,31]. The focus of the LCC analysis was to compare different heating energy solutions for the development (excluding residents' energy demand for household electricity). For all the defined investment options (Section 3.3), cost data was attained from the cost estimators of the construction company and a photovoltaic panel supplier.

3.5.1.2. Use phase assessment. The next step was to estimate the energy demand of the development. The energy demand was attained by performing an IDA ICE building simulation where the energy demand (kWh/m^2/a) for appliances, lighting, air delivery, domestic hot water, cooling and heating were subcategorized. This data was then transformed into MWh/a and further calculated into energy cost per year. The energy costs were attained from the local energy company, including the annual fee, connection fee (excluding VAT) and the transfer fees. Different energy demand categories were combined with the correct energy type, for example, appliances with direct electricity and heating with district heating (or heating with district electricity for the ground source heat pump option). The energy produced by the photovoltaic panels was deducted from the energy demand, thus creating a lower energy demand for these alternatives. As a result, an annual energy cost for each option was obtained.

Maintenance costs for the different energy systems (options to be evaluated) were obtained from the design manager (building services) of the construction company. Furthermore, maintenance and operational costs for the facility management were acquired by performing a building maintenance cost plan for the buildings [48]. Together, these conclude the annual maintenance costs.

An estimated replacement schedule (including component replacement years and costs) for the life cycle works was the last piece of data needed for the assessment. This estimation was obtained by performing a life cycle works plan in accordance with a reference guide [49]. The cost data attained was transposed to the current monetary value (2012). A more accurate replacement schedule for the energy systems was obtained by the design managers (building services) from the construction company.

3.5.1.3. Relevant economic parameters. When all the relevant cost data for the assessment was received, it had to be placed into the life cycle framework (years). In order to make the different options comparable with each other, the cost data had to be indexed and discounted so that each option could be presented in a net present value context and be comparable with each other from a life cycle perspective. Choosing a high discount rate will emphasize the near future; a low discount rate will emphasize the distant future. If the discount rate is zero, timing has no importance whatsoever [24].

Indexation and discounting rates were chosen to reflect a stable macro-economic prospect. The indexation rate of 2.00% was tied to the ECB (European Central Bank) inflation target [50] and the discount rate of 2.60% was tied to Finland's 10-year government bond [51]. These rates are applied to construction costs, energy costs, maintenance costs and life cycle costs. In the sensitivity analysis, the energy indexation will be in focus when analyzing the different energy system options.

3.5.2. LCA

In the study, the GHG emissions of the residential area life cycle are divided into construction phase and use-phase emissions. The GHG emissions of the construction phase consist of construction phase emissions of buildings and infrastructure, including the emissions embodied in the utilized materials as well as those caused by the different energy systems. The use-phase emissions consist of GHGs caused by primary energy consumption of the buildings with different energy systems as well as GHGs caused by the building maintenance. The construction and use-phase activities are presented in more detail in the next subsections of the study.

3.5.2.1. Construction phase assessment. LCA of the construction phase was carried out using the costs of the construction project as primary data apart from electricity and heat, which were assessed using the energy consumption amounts of the construction project. The amounts of energy consumed in the construction process were calculated using the costs of energy and prices of electricity and heat for the construction company. All the primary data of the construction phase was received from the construction company. The buildings' construction costs were divided into 37 cost categories, and the costs of the infrastructure construction were divided into 7 categories.

The ENVIMAT IO model was used as secondary data for modelling the GHG emissions of all construction activities and materials except electricity and heat. The costs of the construction phase were paired with the appropriate sectors from the ENVIMAT IO model. The construction activities and GHG emissions of activities are presented in the supplementary information of the study along with the ENVIMAT sector selection for categories.

For electricity and heat, the hybrid LCA model was used as a modelling application. In the hybrid model, the GHG emissions of the energy production process are based on the local energy provider's carbon intensity. The carbon intensity of the combustion process is 266 g CO_2e/kWh for electricity and heat. The costs of electricity and district heat (taken from statistics of the Finnish Energy Market Authority) were 0.095 €/kWh for electricity and 0.048 €/kWh for district heat. The indirect emissions are then modelled using the lower tiers of the ENVIMAT energy production and supply sector. The costs of the electricity and heat received from the construction company were used as primary data. The carbon intensity of the lower tiers of ENVIMAT is 900 g CO_2e/€ for the electricity production sector and 1170 g CO_2e/€ for the hot steam production sector, which is used for district heating (Mattila T. Email to Säynäjoki A. 17 January 2012) [52]. Accordingly, total life cycle wide production intensities for energy used in the construction phase are 352 g/kWh for electricity and 323 g/kWh for heat.

The GHG emissions caused by construction of various energy systems were assessed using the ENVIMAT IO model. The costs, emissions and sector selection are provided as supplementary information.

3.5.2.2. Use-phase assessment. The use-phase assessment of the study consists of GHGs caused by energy consumption and maintenance activities of the buildings including the energy infrastructure. The primary data used in estimating the energy use related GHG emissions are the estimated energy consumption figures for each energy system, which were received from the construction company. In the data, the estimated energy use of the buildings was divided into six categories: appliances, lighting, blowers, warm water, cooling and heating. The GHG emissions of the electricity and heat consumption were then assessed using the same hybrid LCA model as in the construction phase assessment. The GHG intensity of electricity was used for appliances, lighting and blowers. The GHG intensity of district heat was used in order to assess the GHG emissions of warm water and heat production in district heating scenarios. Warm water and heat are by-products of the CHP (combined heat and power) joint production of electricity and heat. GHG emissions caused by the heating of premises and water in ground heat pump scenarios were assessed using the electricity's GHG intensity and the ground heat pump's efficiency coefficient. Electricity demand for ground heat pump is assumed to be one-third of final energy consumption [46]. Costs, emissions and sector selection are provided as supplementary information.

In order to model GHG emissions related to maintenance, repair and replacement, the costs of these activities were resolved. The building-related costs were retrieved from Kiiras et al. (1993) [53], whereas the construction company provided the cost related to energy systems. The maintenance costs of the buildings and energy systems were converted into GHG emissions using the ENVIMAT sector "Other residential services". Kiiras et al. (1993) name 35 repair and replacement activities for a multi-story residential building as well as their renovation periods, which differ between 5 and 25 years depending on the type of activity [53]. The costs of renovations were reported in year 1990 Finnish marks and then converted to euros using the mark-to-euro exchange rate and the construction costs index 1990–2012. The costs of renovation activities were then converted into GHG emissions using the ENVIMAT sector "Residential construction". The costs, sector allocation and GHG emissions related to maintenance, repair and replacement activities are provided as supplementary information.

4. Results

The results of this study are presented in three phases. The primary results of the study (i.e., the cross-examinations of the LCC and LCA analyses) are introduced first. Secondly, the main results of the LCC analysis are presented in more detail along with an appropriate sensitivity analysis. Finally, the more detailed results of the LCA analysis are portrayed.

4.1. Cross-examinations of the LCC and LCA results

The LCC results on the 25 years life cycle were net present cost of 85.85 €/m^2/a for the district heating option, 86.05 €/m^2/a for the district heating with photovoltaic panels option, 83.78 €/m^2/a for the ground source heat pump option, and 83.89 €/m^2/a for the ground source heat pump with photovoltaic panels option. The LCA analysis with the 25-year life cycle resulted in GHG emissions of 45,832 tons for the district heat option, 44,425 tons for the district heat with the photovoltaic panels option, 35,167 tons for the ground source heat pump option and 33,738 tons for the ground source heat pump with photovoltaic panels option. The LCC and LCA analyses resulted in similar results. The ground source heat pump was the better option on both perspectives on a 25-year time horizon. When a longer life cycle of 50 or 100 years was concerned, the mutual order of the ground source heat pump and the district heating options remains the same. Photovoltaic panels along with district heating or ground source heat pump systems only benefit from an economic point of view on a 100-year life cycle, whereas photovoltaic panels result in fewer GHG emissions on all analyzed life cycles compared to the systems with no photovoltaic panels. The detailed results of all analyzed life cycles are presented in separate LCC and LCA results sections.

When comparing the economical and ecological life cycle outcomes, we detect that they have the same trends (order of breakpoints and final outcome), which are formed in different time frames. The ecological breakpoints occur within the first 10 years, whereas the economical outcome takes up to 32 years to reach the final outcome, excluding the reinvestments at year 50 (high uncertainty due to long time span). Additionally, the carbon emissions have a higher directional coefficient, which means that the operational carbon emissions per annum are relatively higher than the annual costs, thus creating a greater difference between the comparable options in the end (100 years). All the breakpoints of cumulative GHG emissions take place in just a few years' time from the beginning of the use phase. The cumulative comparison between the LCC and LCA outcome is portrayed in Fig. 1.

4.2. LCC main results

The LCC calculation seems to produce surprisingly similar results with all the studied energy systems. The results are within a 2.6% range within a 25-year life span, 3.8% within 50 years and 4.7% within 100 years. With almost all life spans, the ground source heat pump is the most life cycle affordable option. Only with 100 years, the ground source heat pump with building-integrated photovoltaic panels performs around 0.3% better. The most expensive option seems to be the district heat option with (25 & 50 years) or without the photovoltaic panels (100 years).

Starting from the shortest concerned time span of 25 years, the ground source heat pump (3) has the lowest life cycle net present cost with 83.78 €/m^2/a, despite having the second highest initial investment cost. The impact of renewable energy is rather low, since costs generated from energy is relatively small compared to maintenance and life cycle replacements costs. The most significant changes happen within the first 10 years. It is to be noted that the longest time-span (100 years) inherently includes the highest uncertainty, especially because with low depreciation values, the differences are moderate.

When only the investment costs are examined, we can see that the results are almost the opposite. The lowest investment cost option is the district heat option, which appears to be relatively

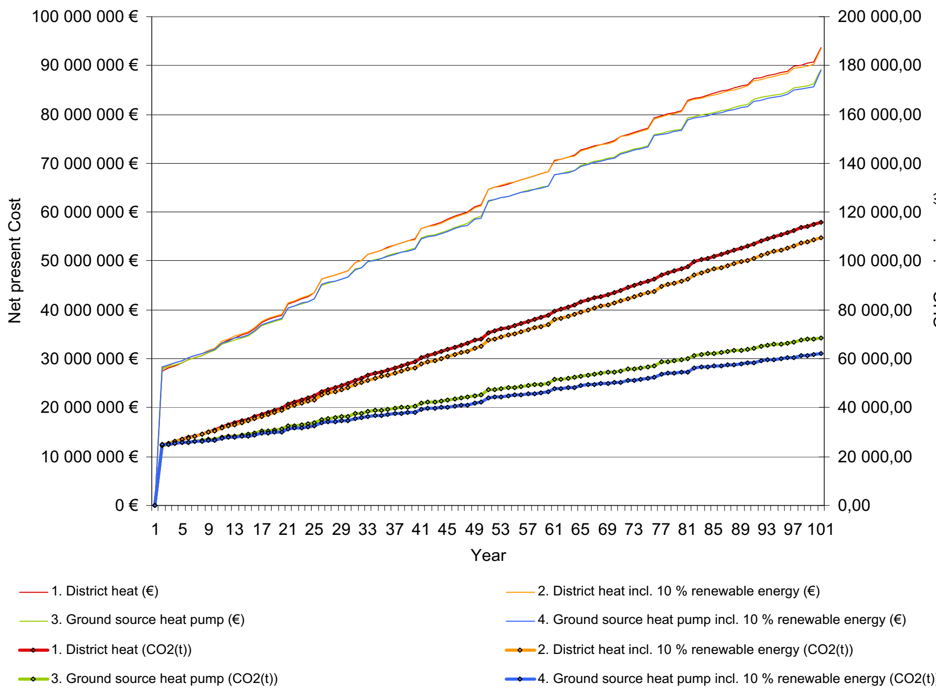

Fig. 1. Cumulative LCC and LCA outcome (100 years).

costly from a life-cycle perspective. Correspondingly, the ground source heat pumps (with or without building-integrated panels) have the highest initial investments and appear to be life-cycle affordable.

There are also several temporal thresholds that affect the outcome. Actually, the LCC results show that already within the first 10 years, the life-cycle economic inclination trends are revealed for each evaluated option. The first breakpoint occurs in the sixth year when the district heating option (1) is exceeded by the ground source heat pump design (3) in terms of life cycle affordability. Simultaneously, district heating with 10% renewable energy (option 2) is exceeded by the ground source heat pump option with 10% renewable energy (4). The second breakpoint emerges in year 10 when the total costs for ground source heat pump with 10% renewable energy (option 4) becomes more life-cycle affordable than the district heating option (1). By year 29 and 32, both options, including 10% renewable energy, become life cycle affordable: ground source heat pump (4) at year 28 and district heating (2) at year 32. These trends continue until year 100 except a few years after year 50, when the renewable energy options fall below life-cycle affordability due to total system reinvestments at year 50.

The total life cycle costs (net present costs) are presented by category in Table 2 and illustrated in Fig. 2. Note that the different energy design options mostly affect the energy costs and thus generate additional cost savings for the options including renewable energy.

When examining the first 25 years, it is evident that the energy systems that include building-integrated photovoltaic panels do not attain life cycle affordability. The ground source heat pump (option 3) is the most life cycle affordable within the first 25 years.

Table 2
Life cycle costs categorized (25/50/100 years).

	Net present cost	1. District heating	2. District heating incl. 10% renewable energy	3. Ground source heat pump	4. Ground source heat pump incl. 10% renewable energy
25 years	Investment cost	27,046,313 €	27,558,156 €	27,433,237 €	27,945,080 €
	Energy cost	3,015,481 €	2,564,239 €	1,309,653 €	858,411 €
	Maintenance cost	9,288,493 €	9,288,493 €	9,288,493 €	9,288,493 €
	Life cycle replacement cost	6,893,942 €	6,939,029 €	7,094,186 €	7,094,186 €
	Total	46,244,228 €	46,349,917 €	45,125,568 €	45,186,170 €
	Tot. NPC/m^2/a	**85.85** €	**86.05** €	**83.78** €	**83.89** €
50 years	Investment cost	27,046,313 €	27,558,156 €	27,433,237 €	27,945,080 €
	Energy cost	5,619,695 €	4,778,754 €	2,440,690 €	1,599,749 €
	Maintenance cost	17,310,176 €	17,310,176 €	17,310,176 €	17,310,176 €
	Life cycle replacement cost	14,651,533 €	15,086,004 €	15,061,110 €	15,450,493 €
	Total	64,627,718 €	64,733,091 €	62,245,212 €	62,305,499 €
	Tot. NPC/m^2/a	**59.99** €	**60.09** €	**57.78** €	**57.83** €
100 years	Investment cost	27,046,313 €	27,558,156 €	27,433,237 €	27,945,080 €
	Energy cost	9,811,040 €	8,342,899 €	4,261,032 €	2,792,891 €
	Maintenance cost	30,220,646 €	30,220,646 €	30,220,646 €	30,220,646 €
	Life cycle replacement cost	26,517,893 €	27,276,406 €	27,235,443 €	27,948,868 €
	Total	93,595,891 €	93,398,107 €	89,150,358 €	88,907,486 €
	Tot. NPC/m^2/a	**43.44** €	**43.35** €	**41.38** €	**41.26** €

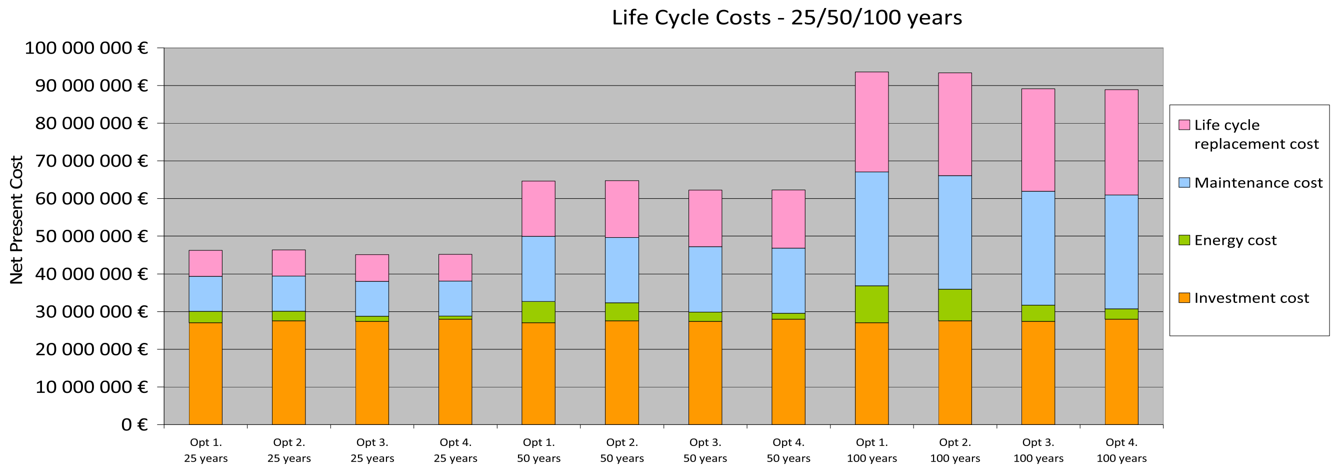

Fig. 2. Life cycle costs (NPC) for the evaluated options (25/50/100 years).

When examining the time periods of 50 and 100 years, the established trends continue until the end. Note that these results are acquired with an indexation rate of 2% and a discount rate of 2.6%.

4.2.1. Sensitivity analysis for LCC results

Sensitivity analysis for the LCC results is to be made in order to understand how indexation and discount rate affect the outcome, especially when one of the chosen time periods is up to 100 years. The key parameter to be examined is the energy indexation, since the evaluation focuses on different energy systems and their life cycle costs.

At first, the effects of indexation and discount parameters were analyzed by establishing a buffer zone. The buffer zone was drawn to include indexation and discount changes between 0 and 8 percent, thus portraying nearly all possible future scenarios for each option. Certain years may have a negative rate, but in the long run, the average is assumed to be positive.

The energy indexation was tied to the general indexation of 2% in the estimation, which means that the options that include renewable energy (2 & 4) obtain a life cycle affordable status (100-year period). The sensitivity analysis reveals that in order for the options excluding 10% photovoltaic panels (options 1 & 3) to become life cycle affordable, the annual energy indexation would have to further changed from 2.00% by −0.32% (100 years), +0.45% (50 years) and +1.44% (25 years) against the district heat option and −0.40% (100 years), +0.27% (50 years) and +0.86% (25 years) against the ground source heat pump option. Thus, if the realized indexation falls below +1.68%, the options that include photovoltaic panels become economically disadvantageous from a life cycle perspective (100-year period).

Additionally, the sensitivity analysis demonstrates that in order for the district heating options (1 & 2) to surpass the ground source heat pump options (3 & 4), the annual energy indexation would have to decrease significantly by 5–8% during the different time periods 25, 50 and 100 years.

It is important to point out that the same sensitivity principles effect the annual property maintenance cost index, which is this study represents a relatively more significant part of the life cycle costs (Table 2 and Fig. 2), and thus have a greater impact on the final life cycle outcome.

4.3. LCA main results

According to the assessment, the lowest life cycle GHG emissions are reached with the ground source heat pump with photovoltaic panels option during the time periods of 25, 50 and 100 years. The highest GHG emissions during the three time horizons are caused by the district heating option, with the district heating option with photovoltaic panels causing the second most emissions and the ground heat pump option causing the third most emissions.

The amount of GHG emissions after 25 years ranges from approximately 33,800 tons with the ground source heat pump with photovoltaic panels option to 47,700 tons with the district heating option. During the 50-year time horizon, the ground source heat pump with photovoltaic panels option causes the lowest GHG emissions (44,100 tons) and the district heating option causing the most GHG emissions (70,500 tons). If the whole 100-year period is taken into consideration, the ground source heat pump with photovoltaic panels option causes the lowest GHG emissions (62,300 tons). The district heating option causes the most GHG emissions (115,900 tons) during the 100-year life cycle. The GHG emissions of different energy systems on three different time horizons are presented in Table 3.

The construction phase emissions of the residential area differ between different energy solutions. The district heating option causes construction-phase emissions of approximately 24,500 tons. The corresponding figures are approximately 24,700 tons for both the ground source heat pump option and for the district heating with photovoltaic panels options and 24,900 tons for the ground heat pump with photovoltaic panels option. The share of the use phase of the total life cycle emissions differs from approximately 20% for the district heating option to approximately 40% for the ground source heat pump with photovoltaic panel's option.

The carbon payback times of different systems are only a few years. The cumulative GHG emissions of the district heating option with photovoltaic panels fall below the emissions of the district heating option in four years. The corresponding carbon payback times compared to district heating option are one year for a ground heat pump and two years for a ground heat pump with photovoltaic panels.

Table 3
GHG emissions of different energy systems on three main time horizons.

Year	1. District heating	2. District heating incl. 10% photovoltaic panels	3. Ground source heat pump	4. Ground source heat pump incl. 10% photovoltaic panels
25	45,832	44,425	35,167	33,738
50	68,857	65,946	46,916	43,983
100	112,599	106,483	68,087	61,949

The options with ground source heat pumps have short carbon payback times of only a year or two, but the result in significantly lower in GHG emissions during the 100-year time period compared to the district heating options. The ground source heat pump option results in 40% lower emissions during the 100-year period. The option of ground heat pump with photovoltaic panels results in 42% lower emissions than the option of district heating with photovoltaic panels. The comparison of district heating and ground source heat pump with photovoltaic panels has the most contrast and results in 45% lower emissions in favour of the ground heat pump with photovoltaic panels option during the 100-year period.

5. Discussion

The purpose of this study was to examine both the ecological and economical life cycle outcome (cost and emissions) of a new residential development in order to add valuable information for decision makers and future residents. Li et al. (2013) recommend that life cycle cost and environmental impact assessments should be developed further in order to promote more energy-efficient building types and renewable energy technologies [54]. The results show that economical and ecological aspects clearly support each other from a life cycle perspective and at the same contradicts the investment-cost approach. This study reveals that by selecting a slightly higher investment, a significant proportion of energy costs and emissions can be cut (e.g., option 4). A ground source heat pump with building-integrated photovoltaic panels is more life cycle-affordable due to lower energy costs, thus generating lower emissions. Similar results are attained from residential buildings in Denmark where a combination of ground source heat pump and photovoltaic technology results in the most cost-optimal solution [55,56]. A summary of life cycle costs and emissions are portrayed in Table 4.

The results show that by applying a life cycle management approach through LCC and LCA analyses, cost and emission savings can be achieved with existing technological systems. An additional investment in the investment phase appears to add value during its life cycle, both economically and ecologically. Life cycle management is to be further emphasized and employed in urban residential development if viable solutions are to be recognized and implemented.

Research combining LCC and LCA analyses particularly for residential energy demand in Nordic conditions, has not been carried out in this extent. However, there are comparable studies of LCC and LCA combinations within the building and energy sector that are in line with this study. Kosaero & Ries (2007) have assessed the life cycle impact of green roofs and concluded that the environmental impact is significant during the life cycle, even though energy reduction is relatively small compared to the overall building demand [57]. An operational LCC and LCA regarding water use in multi-occupant buildings is performed by Arpke & Hutzler (2005), which suggests that high-efficiency fixtures are both economically and environmentally justified and suitable for long-term owners who can benefit from operational cost savings [58]. Concerning the life cycle impact of renewable energy options, Heetae & Tae Kyu (2011) have assessed the correlation between LCC and LCA of different energy generation systems, which revealed that energy resources are mainly inversely proportional to GHG emissions and the corresponding cost (except nuclear power). For example, solar photovoltaic panels have a high cost with low emissions compared to coal, which has low costs and high emission rates [59]. However, Heetae & Tae Kyu (2011) did not consider the energy demand side in their study; only electricity production was evaluated [59].

A critical matter concerning the results of the study is obtaining reliable data since analyses require a significant amount of data whose outcome depends on the accessibility, quality and accuracy of the input data. The data considered to have the highest uncertainty are future operational costs and life cycle performance information. In this study, a cross-check for operational and maintenance costs between data acquired from the construction company and the established maintenance plan was carried out in order to reduce overall uncertainties in LCC and LCA modelling.

Energy indexation is another debatable factor in the LCC study. The sensitivity analysis shows that if the annual energy indexation falls below 1.68%, the renewable energy options would no longer be life cycle affordable. An important question arises: What is the best realistic estimation of the annual energy increase for the future? In Finland, historical data from 1996 reveals that the annual energy price indexation (in real terms) for electricity is about 2.49% per year and 2.51% per year for district heating [60]. If these rates are applied, they will further favour the renewable energy options and have a positive affect on their payback time.

Estimated long-term price developments imply that the annual price increase for oil will be around 2.80%, and for coal about 2.00%. For household electricity, the annual escalation would be around 1.40%. Note that these future price estimates are in line with political guidelines and targets towards a more sustainable Europe [61].

Furthermore, a questionable matter is the future replacement costs for the building-integrated photovoltaic panels. The development of photovoltaic systems has been rapid in both cost and efficiency, which is predicted by the European Commission to continue in the future [61]. Therefore, it is difficult to predict costs and replacement measures for the photovoltaic panels, but assuming the current cost level, the future cost impact should not be underestimated. The future outlook for photovoltaic systems indicates that if economic incentives are maintained during the next decades, photovoltaic technologies will probably have a significant role in the future energy mix while simultaneously decreasing the environmental impact of energy generation [62].

The GHG modelling of the study is based on multiple assumptions that have a significant effect on the results. Among the most important are advances in the energy production technology, the carbon intensity of the maintenance, future renovation actions, and the operating life cycle of the buildings. In addition, the IO LCA models are not suitable for modelling distinctive products because

Table 4
LCC and LCA results (25/50/100 years).

		1. District heating	2. District heating incl. 10% photovoltaic panel's	3. Ground source heat pump	4. Ground source heat pump incl. 10% photovoltaic panel's
25 years	Net present cost (€)	46,244,228 €	46,349,917 €	45,125,568 €	45,186,170 €
	GHG emissions (tons)	45,832	44,425	35,167	33,738
50 years	Net present cost (€)	64,627,718 €	64,733,091 €	62,245,212 €	62,305,499 €
	GHG emissions (tons)	68,857	65,946	46,916	43,983
100 years	Net present cost (€)	93,595,891 €	93,398,107 €	89,150,358 €	88,907,486 €
	GHG emissions (tons)	112,599	106,483	68,087	61,949

the method is based on national average data [35]. The IO LCA covers a significant share of the construction phase analysis. However, the building type in the study represents current general multi-story house construction technology in Finland, which reduces the uncertainties related to the assessment method from this perspective.

Allocation of district heat GHG emissions between joint production electricity and heat causes additional uncertainties in the study. Two commonly used allocation methods remain in Finland: the energy method and the shared benefits method. The allocation method used in the study is the energy method, which allocates the GHG emissions of the joint production process based on the shares of generated electricity and heat [44]. The shared benefits method allocates GHG emissions for electricity and heat by defining the alternative production methods for combined production based on separate production and calculating the GHG emissions for electricity and heat accordingly [44]. In general, the energy method results in approximately equal GHG emissions per kWh produced, whereas the shared benefits method considers district heat as a by product of joint production electricity and thus results in higher GHG emissions for electricity, and a smaller share of production-phase GHG emissions is allocated for heat [44]. Changing the joint production GHG emissions allocation method to the shared benefits method has a significant affect on the results of the study. When the shared benefits method is used, combustion-phase GHG emissions for heat decrease by 35 percent and the corresponding GHG emissions for electricity increase by 46 percent compared to the energy method. However, the allocation method does not change the mutual order of the GHG emission quantities of different energy systems on any of the study's life cycle periods and thus does not have an affect on the conclusions of the study.

The carbon intensity of the energy production is likely to decrease in the future along with technical advancements in energy production processes. According to a scenario made by Finnish Energy Industries, the carbon intensities of the electricity and district heat production are going to decrease 85–90 percent from the year 2010 level by the year 2050 [63]. This would significantly decrease the importance of GHG emissions occurring in the distant future. However, the carbon payback times of the different energy options of the study are only a few years, so future decreases in energy production intensities will not change the mutual order of the options, although the GHG emissions of the district heating solutions decrease most radically in the future due to a combination of high energy consumption and lower energy generation intensity in the future.

The European Commission has established guidelines for a comparative methodology framework for calculating cost-optimal designs [64]. In this framework, there is a cost group labelled *cost of greenhouse gas emissions*. This cost group implies that in the future, there may be costs for generating greenhouse gases. In this report the recommended minimum price is around 0.03–0.04 €/CO_2 (kg). If costs for producing greenhouse gas emissions would be applied, this would further enhance the connection between LCC and LCA. In order to execute an LCC model, an LCA would have to be executed to obtain the data for the costs of greenhouse gas emissions.

One general limitation of the study is that a streamlined LCA [37] is employed where only the GHG emissions are accounted from a wide scope of economic and environmental assessments. While climate change is inevitably one of the most relevant environmental concerns at the moment, other impacts may become equally important in the near future. For example, Rockström et al. (2009) claim that humans would already have exceeded the planetary boundaries in three impact categories: climate change, biodiversity loss, and the global nitrogen cycle [65]. Furthermore, GHGs seem to indicate rather poorly at least some of the other environmental impacts [66]. Actions for GHG mitigation may even increase the severity of other impacts. For example, Greening et al. (2012) studied the environmental affects of domestic heat pumps and gas boilers in the UK. Their study indicated that even though replacing gas boilers with heat pumps leads to lower GHG emissions, the use of heat pumps does not offer significant environmental advantages since they qualify as worse for most environmental impact categories [67].

It is also well-known that besides the GHG emissions, the construction and operation of buildings inflict other environmental effects. For example, Junnila et al. (2003) included four other environmental aspects besides GHGs in their study, which focused on the life cycle environmental impacts of office buildings. The other aspects were acidification, summer smog, eutrophication and heavy metals [68]. Blengini et al. (2010) studied cumulative energy demand, non-renewable energy demand and potentials for global warming, ozone depletion, acidification, eutrophication and photochemical ozone creation in their LCA of an Italian low-energy residential building [69]. Passer et al. (2012) studied the potential of acidification of land and water, eutrophication, global warming, depletion of the stratospheric and tropospheric ozone layers plus uses of renewable and non-renewable energy resources in their LCA of technical building equipment on residential buildings [70]. Thormark (2000) included global warming potential, acidification, eutrophication and photochemical ozone formation in his comparison of two similar houses built with either new or recycled building materials [71].

This said, concentrating on GHGs in the current study is still relatively well-justified because climate change is currently one of the hottest environmental issues globally and the greenhouse gas mitigation targets set by the EU for the years 2020 and 2050 also set significant mitigation challenges for the European building stock. Improving the building stock can have a significant impact as well, according to earlier research. For example, Broin et al. (2013) studied the energy efficiency improvements of buildings for the EU-27 under three different scenarios. Their study indicates that the requirements set for 2050 can be reached within the EU-27 building stock with strict energy efficiency policies. However, massive improvements have to be accomplished in many industries, for example replacing all fossil fuels with carbon-neutral substitutes in electricity and district heat production [72].

6. Conclusions

The results of this study show that when aligning economical and ecological interests, they support each other in a life cycle framework. Consequently, why does economical and ecological life cycle viability not appear interesting by professional real estate investors and residents? Lützkendorf & Lorenz (2005) state that the perception of how properties are valued in decision-making processes is changing and that the life cycle of the building should be a seen as a key performance index in the future [73]. As for residents, the cost and emission savings (with current energy prices) generated during the life cycle does not weigh heavily enough in decision-making next to conventional value parameters such as accessibility, service infrastructure, social factors and the physical environment [74].

The aim of this study is not to evaluate which technical energy design solution is more sustainable in the long run, but to portray that economic and environmental benefits support each other in urban residential development, and additionally that a methodological life cycle assessment framework should be used in decision-making processes. Kats et al. (2003) share the view that such benefits (energy savings) should be evaluated from a life cycle cost methodology and not just in upfront costs [75]. Additionally, Passer et al. (2012) suggest that technical equipment should be analyzed along with the conventional construction products in order to enhance the conventional LCA [70].

Our modern society is dependent on oil as its primary source of energy. It has been estimated that within the next 20–40 years, the amount of oil will not be able to provide our society with the demand for sufficient energy. The World Energy Outlook report estimates that our oil peak was reached in 2006 [76]. Therefore, it is imperative that increasingly more renewable energy production is added to the energy supply side in order to decrease (and hopefully eliminate) our future dependency on oil. There is a significant demand for eco-efficient concepts in urban development [77]. In the end, self-sufficient urban areas are the ultimate solution.

Suggested further research should focus on possibilities to optimize facility management by taking a life cycle perspective from both the economic and ecological aspects. Facility management services have a significant impact on environmental indicators [78]. If an economic incentive to save money would be exposed, the importance of life cycle management in real estate development would further improve.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2013.10.030.

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