Master’s Thesis Internship – master Sustainable Business and Innovation

Relating environmental performance of buildings to policies for sustainable urban design

Combing the quantitative and qualitative lense on policy-making for sustainable buildings in the Netherlands by LCA interpretation of BENG buildings and research on the social acceptance of policies for sustainable buildings

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Summary

Sustainable urban design has become increasingly important due to the growing environmental impact of cities. There is a need for practical environmental performance assessment tools that can be applied to sustainable urban design. Heating of buildings contribute to 32% of the Dutch national energy consumption and has therefore substantial influence on an urban scale. The Dutch government introduced BENG buildings regulations for newbuild buildings—which are compulsory from 2020—however, the LCA study on BENG buildings from W/E adviseurs (2019) has not yet been related to sustainable urban design policies. This research investigates how to relate LCA results of BENG buildings to policies for sustainable urban design and how to subsequently develop policies for sustainable buildings in the Netherlands.

The LCA interpretation compares the environmental impacts of the BENG building's materials from terraced buildings with a sloping roof, terraced buildings with a flat roof and corner buildings for scenarios with all-electric, heat and gas electricity generation systems. The environmental impacts are presented in annual shadow costs per m^2 of gross floor area. The LCA interpretation shows the all-electric buildings have the lowest shadow costs. The results show the gas buildings have 21% to 43% larger environmental impact than the all-electric buildings and the heat buildings have 4% to 16% larger environmental impact than the all-electric buildings depending on the building type.

Furthermore the LCA interpretation shows 81% to 147% of the shadow costs differences between electricity generation systems are caused by the building's number of PV panels. Gas buildings need a larger number of PV panels to accomplish the almost energy-neutral design in accordance with the BENG regulations and are still less sustainable compared to the all-electric and heat buildings regarding the building's materials, because the larger number of PV panels from gas buildings causes additional environmental impacts from the building's materials. The gas scenario is less sustainable than the all-electric scenario, because of the technological reason that a heat pump in the all-electric scenario can reach an efficiency of 400%, which is substantially larger compared to a typical 70% to 80% efficiency of a gas boiler in the gas scenario. Therefore, the LCA interpretation—though it is based on the newbuild BENG buildings—supports the policy from the Dutch government that aims for natural-gas free buildings. Two natural-gas free policy options for existing buildings are the transition to the heat scenario or to the all-electric scenario.

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1 Introduction

1.1 Problem definition

Since ancient times, cities around the world have been spatially divided into districts or neighborhoods - the building blocks of our cities (Rohe, 2009; Searfoss, 2011). Cities are growing at high rate, due to rapid urbanization in Europe and the rest of the world (Potjer, Hajer, & Pelzer, 2018). More than 50% of the world's population lives in cities since 2014 (Ameen, Mourshed, & Li, 2014) and by the year 2050 this is predicted to increase to 69% of the global population (Shen, Ochoa, Shah, & Zhang, 2011; United Nations [UN], 2015). Likewise, the growth of cities is accelerated by the exponentially increased human population in the past 60 years, from about 2.5 billion in 1950 to more than 7 billion nowadays (LEED, n.d.). Rapid urbanization goes hand in hand with growing environmental impact caused by cities. Cities are accountable for global CO2 emissions, the depletion of natural resources and agricultural lands (Ameen et al., 2015). In 2011 cities contributed to 70% of the global CO2 emissions (Ameen et al., 2015) and this number is projected to increase in the future (Ameen et al., 2015). So, sustainable urban design—which is the sustainable focus on design, planning, engineering, and policy (Larco, 2016)—has become increasingly important (Potjer et al., 2018) (Dehghanmongabadi, Hoşkara. & Shirkhanloo, 2014). Sustainable urban design is seen as indispensable for informed decision-making (Ameen et al., 2015). This is because it is fundamental to successfully deal with the fast growth of urban settlements and the growing environmental impact caused by cities.

Sustainable urban design is generally considered as fundamental to shape the future of a city. It determines the pattern of a city's resource usage and resilience to change, from climate or otherwise (Ameen et al., 2015). The urban design of cities impact multiple environmental issues such as, the depletion of energy, water and material resources and accelerating climate change (LEED, n.d.). Therefore applying sustainable urban design contributes to preserving natural systems and resources as well as economic and social prosperity, which makes green neighborhoods an integral part of the solution to the environmental challenges facing the planet (Dehghanmongabadi et al., 2014; LEED, n.d.).

Now that sustainable urban design becomes increasingly important, the literature highlights a need for a framework to improve the usability of environmental performance assessment tools in architectural practice, since current environmental performance assessment tools are not adopted to architects' needs (Meex, Hollberg, Knapen, Hildebrand, & Verbeeck, 2018; Simons, personal communication 19-02-2020). Practical environmental performance assessment tools for architects and designers are essential to improve environmental performance since most influential design decisions are made by architects in early project stages (Meex et al., 2018). Since the beginning of the 21st-century, environmental engineers and scientist began to design tools for sustainability assessment at a neighborhood scale (Sharifi & Murayama, 2013); however, the quantitative literature regarding calculating the environmental performance of an entire neighborhood is sparse (Meex et al., 2018). The main methodology for quantitative environmental performance assessment is Life Cycle Assessment (LCA), a standardized methodology that evaluates the potential environmental impacts of a product or a service throughout its whole life cycle (Du & Karoumi, 2014). LBP|SIGHT has a need for practical LCA applications (Simons, personal communication 19-02-2020). Consequently, LBP|SIGHT a Dutch consultancy company with expertise in sustainable urban design, hired me for a graduation internship to research LCA applications for policy-making.

A LCA on buildings can be related to policies for sustainable urban design. In the Netherlands there is an ongoing transition towards natural gas-free buildings and the Dutch government aims towards the increased use of renewable energy instead of fossil fuels (Rijksdienst voor ondernemend Nederland, n.d.). The transition towards renewable and sustainable energy is accompanied by a transformation of communities and neighborhoods (Van der Schoor & Scholtens, 2015). Nevertheless, governments have run into difficulties when implementing renewable energy as social acceptance has been a constraining factor (Wüstenhagen, Wolsink, & Bürer, 2007). LCA has an interlinkage with policies for sustainable urban design. LCA on buildings can be used to calculate, compare, or evaluate how much environmental impact can be saved by implementing policies for sustainable transitions in neighborhoods. Consequently, environmental performance assessment on buildings can be key for governmental actors since their policies aim to reduce environmental impact.

Sustainable design for Dutch buildings is the focus of the LCA and the policies in this research. Dutch buildings have significant environmental impacts, since 32% of the total final energy consumption in the Netherlands is for heating purposes in the built environment (Schoots, Hekkenberg, Hammingh 2017) and 6% of the total greenhouse gas emissions are caused by buildings (Edenhofer et al., 2014). The Dutch government has introduced numerous policies for sustainable urban design of buildings, like sustainable newbuild standards and policies for the natural gas-free transitions (Rijksdienst voor ondernemend Nederland, 2016; Scholte, De Kluizenaar, De Wilde, Steenbekkers, & Carabain, 2020). An major issue addressed by the Dutch government is that 7.7 million households need a transition towards natural gas-free living (Scholte et al. 2020). This research will zoom-in on how LCA of Dutch buildings can be related to sustainable transitions and policies.

In 2020 the regulations from The Dutch government for BENG buildings which stands for almost energy-neutral buildings are compulsory for all newbuild projects (Rijksdienst voor ondernemend Nederland, 2016). Since BENG buildings are almost energy-neutral buildings they are sustainable in the usage phase, due to its energy-neutrality (Van der Leij, personal communication 2 October 2020). Nevertheless, a drawback of the focus on energy-neutrality is that the environmental impacts of building's materials like installations for PV panels and insulation materials can increase to accomplish the almost energy-neutral building's design (Van der Leij, personal communication 2 October 2020). Therefore, W/E adviseurs (2019) in cooperation with LBP|SIGHT conducted an LCA on BENG building's materials comparing multiple types of buildings and electricity generation systems. Since the BENG buildings are a compulsory standard since 2020 it is valuable for policy-making to gain insights in the environmental performance of BENG buildings. However, the LCA study on BENG buildings from W/E adviseurs (2019) has not yet been related to sustainable urban design policies.

1.2 Aim

There is a need for practical environmental performance assessment tools in literature as well as within the company LBP|SIGHT and there is a need for insights on policy-making for sustainable buildings caused by the new BENG buildings regulations.

Therefore, this research has the following research question: ***How to relate LCA results of BENG buildings to policies for sustainable urban design and how to subsequently develop policies for sustainable buildings in the Netherlands?***

This question is answered in three steps: 1) Review of LCA methodological advantages, disadvantages related to sustainable urban design and an strategy for interpretation of LCA results 2) Interpretation of LCA results of BENG buildings in The Netherlands and relating them to policy making 3) Development of a methodology for policy design of sustainable buildings.

A scientific contribution from this research is the practical application of LCA by interpretation of LCA results from BENG buildings and relating them to policy-making for sustainable buildings, which has not been done before. This builds on previous literature since it was highlighted that environmental performance assessment tools are not adapted to architect's needs (Meex, et al., 2018). In continuance of this aim a scientific contribution of this research is the policy-recommendations for sustainable buildings in the Netherlands. This policy-recommendations are made in an innovative way by combining LCA interpretation of Dutch BENG buildings, social acceptance of renewable innovations literature, policy evaluation and interviews with sustainable design experts.

The practical relevance of the research is that employees from LBP|SIGHT can use the findings to provide consultancy advice, particularly to governmental organizations regarding policies for sustainable buildings, by combining the knowledge on LCA interpretation of BENG buildings and social acceptance of the innovation. Furthermore, this research includes a policy design methodology which aims to effectively increase the adoptions of sustainable innovations for buildings.

2 Theoretical framework

The theoretical framework explains literature regarding LCA (2.1), social acceptance of renewable energy innovations (2.2) and sustainable urban design (2.3). Consequently a new conceptual model regarding policy design for sustainable buildings (2.4) is introduced by combining all the literature parts.

2.1 Life cycle assessment

Using LCA is relevant to analyze the environmental performance of Dutch buildings. The LCA is fitting with the research steps since LCA methodology mainly focuses on the environmental side of sustainability and describes how to assess environmental performance quantitatively. LCA methodology has the following principles by the new international ISO 14040 standard (Finkbeiner, Inaba, Tan, Christiansen, & Klüppel, 2006, p. 83):

LCA is a iterative technique with an environmental focus to compile an inventory of inputs and outputs of a product, evaluate the associated impacts and interpret the results of inventory and impact assessment. The LCA includes all life cycle stages of products namely raw material acquisition, production, use, and disposal. The LCA results will include impacts on resource use, human health, and ecological consequences.

The LCA procedure is divided into the systematic steps 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation.

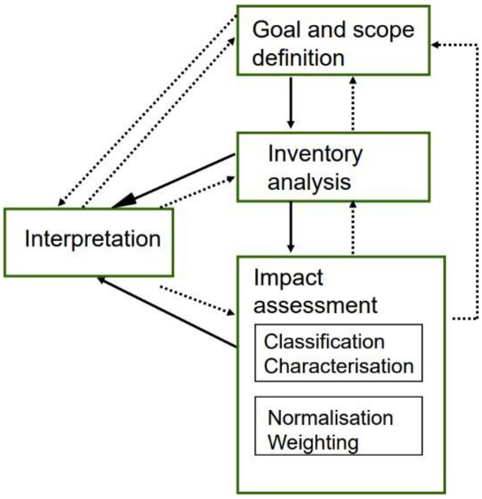

Figure 1: ‘LCA procedure’

The first three steps goal and scope definition, inventory analysis and impact assessment are executed by LCA experts in the study from W/E adviseurs (2019) and the interpretation step is executed in this research.

Step 1) Goal and Scope definition

During the goal definition, intended applications of study, reasons for carrying out the study and the target audience are defined. The scope definition includes the system boundaries, the functional unit and the impact assessment methodology (European Commission, 2010; Hoefnagels, 2018). Hoefnagels (2018), an LCA expert, uses temporal, geographical and technological aspects to define the system boundaries. An overview of the system boundaries is given in table 1.

Table 1: defined system boundaries (Hoefnagels, 2018)

Scope definition	Specific steps to define system boundaries
temporal	- ***Old data***: Define: how recent your own input data are - ***Minimum time***: Define: For what amount of time are the used input data causing emissions - ***Reference year:*** Define: For what reference year the results are valid - ***Temporal scope for impact:*** Define: what temporal scope for impact is used
geographical	- ***Geographical region:*** define for what region data are collected and valid
technological	- ***Technology mix:*** Define the assumptions made regarding the used technology

To further define the focus of the research the functional unit and the type of impact assessment methodology are explained.

Functional unit

The functional unit is a detailed quantitative and qualitative description of the studied object(s) and it's technical specifications (European Commission, 2010, p. 11). It indicates how much of this function is considered in the LCA study and it can be chosen arbitrarily (European Commission, 2010). Based on the functional unit the Reference flow isdetermined. References flows are: volume flows, used to calculate the inputs and outputs of the system (European Commission, 2010).

A square meter of gross floor area is chosen as the functional unit of a building (W/E adviseurs, 2019). This functional unit is chosen since a square meter of gross floor area provides living space which is the function of a building .

Type of impact assessment methodology

Within LCA a distinction is made between attributional LCA studies, which are descriptive and aimed to account for the environmental performance of a product or process (Weidema, 2003). Consequential LCA studies are change-oriented and compare multiple processes (Weidema, 2003). This research will perform the interpretation step of an attributional LCA study.

Step2) Inventory analysis

The inventory step consists of data collection and compiling the inventory and elementary flows.

Data collection: The integration of GIS in LCA

Several studies conclude that the integration of Geographic Information Systems(GIS) in LCA is useful to account for the impact of spatial units. These studies highlight that current LCA measures are inadequate to spatially account such impacts (Hiloidhari et al., 2017). However, the integrated use of GIS and LCA could address such issues by allocating the impacts into spatial units (Bengtsson, Carlson, Molander, & Steen, 1998; Geyer, Stoms, Lindner, Davis, & Wittstock, 2010; Gasol, Gabarrell, Rigola, González-García, & Rieradevall, 2011; Gorniak-Zimroz & Pactwa, 2015). GIS has not been integrated in the LCA study from W/E adviseurs (2019).

Data collection: Foreground and background systems

In the inventory stage, the decision should be made to either use a foreground system or background system for the analysis. A foreground system uses primary data—which is technological and time-specific data—during the LCA study, while in an background system, secondary data is used. Secondary data is non-primary data derived from other sources such as literature or databases (Manfredi, Allacker, Pelletier, Chomkhamsri, & De Souza, 2012). The quality of LCA with the use of a foreground system is assumed higher compared to background systems, since primary data is more accurate. Nevertheless secondary data is applicable for the use of multiples case-studies since it is based on average data. Average data is technology specific or generic data from third parties (European commission 2010, page 126) and is applicable for the generic environmental performance assessment of buildings. The study from W/E adviseurs (2019) uses primary data according to the BENG buildings regulations designed by the Dutch government to perform the inventory analysis (Rijksdienst voor ondernemend Nederland, 2016).

Compiling of the inventory and elementary flows

Elementary flows consist of both the environmental loads and environmental interventions crossing the system boundaries. The goal of the inventory is to compile the elementary flows per functional unit, this step consists of the development of a flowchart with the collected data. There is a distinction made between two different types of elementary interventions; Positive emissions are elementary interventions originating from the production process to the environment, like emissions. Negative emissions are elementary interventions entering the product systems, like resources or land use. Positive and negative emissions should be taken into account because they both impact the environmental performance.

Step3) Impact assessment

The impact assessment step consists of selection, classification and characterization. Optional steps of impact assessment are normalization and weighting. The goal of the impact assessment step is to express the environmental impact in impact categories[1] or shadow costs. The Dutch National Environmental Database (NMD version 3.0) is used for the impact assessment in combination with the “SKB bepalingsmethode” version 3.0 from the Dutch Quality Building Foundation which is used for the weighting step. Both the “NMD version 3.0” and “SKB bepalingsmethode version 3.0” were released in 2019 and are standards for LCA analysis in the Netherlands (Nationale Milieu Database, 2019).

Selection

In the selection process, the used impact categories are determined. The impact categories that should be checked for all LCAs according to the International Life Cycle Data handbook[2] are (European Commission, 2010, p. 109): Climate change, Ozone depletion, Human toxicity, Respiratory inorganics, Ionizing radiation, Photochemical ozone formation, Acidification, Eutrophication, Ecotoxicity, Land use and Resource depletion. The impact categories from EN15804 standard for LCAs in the Dutch building sector are used by W/E adviseurs(2019), and these impact categories are similar to the impact categories as described in the International Life Cycle Data handbook (Bouwkwaliteit, 2019).

Classification

The classification consists of assigning the positive and negative emissions from the inventory data to impact categories by checking if there is an impact for each impact category.

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[1] The impact categories represent environmental issues of concern to which life cycle inventory results may be assigned

[2] The International Life Cycle Data Handbook developed by the European Commission, Joint Research Centre and the Institute for Environment and Sustainability (European Commission, 2010)

Characterization
Subsequently, in the characterization step, the impact in each category is calculated.

Normalization
The normalization, is an optional step of the impact assessment that supports the interpretation of the impact profile and is a first step to a aggregated results that additionally requires the weighting step(European Commission, 2010, p. 281).

Weighting
In the weighting process, normalized environmental performance results are multiplied with a weighting factor, which reflects the perceived relative importance of the environmental impact categories compared to each other (European Commission, 2010, p. 283). Since the weighting step is subjective it cannot be considered fully scientific.

Normalization and weighting are in addition optional steps under ISO 14044 that are recommended to support the results interpretation (European commission, 2010 p. 119). In the LCA from W/E adviseurs (2019) both normalization and weighting are performed and the LCA results are expressed in shadow costs .

Shadow costs
Applying weighting can be done by calculating shadow costs. The shadow costs are constructed prices for goods or production factors that are not traded in markets, like environmental quality (De Bruyn et al., 2010). Shadow costs indicate the value of environmental quality to society (De Bruyn et al., 2010). This way the shadow costs represents a certain price in terms of damage caused to the environment per set amount of emissions (De Bruyn et al., 2010). Shadow costs, therefore, are useful for comparing the relative severity of different environmental impacts (De Bruyn et al., 2010).

Therefore, expressing LCA results in shadow costs provides a single monetary value to the LCA analysis. Shadow costs are useful for interpretation of LCA results which is problematic when results are expressed in impact categories that could point to different direction. Using shadow prices is one way to overcome this problem, as the results are expressed in a monetary value, making comparison easy for decision makers (Ligthart, & van Harmelen, 2019).
Using the weighting step of LCA to express environmental impact in shadow costs is an optional, controversial, but nevertheless important tool (Johnsen & Løkke, 2013). The weighting step is controversial (Eldh & Johansson, 2006) since it is not an exact science, and some researchers discourage its use completely (Schmidt & Sullivan 2002). Nevertheless, without weighting, the most important impact categories in LCA cannot properly be identified, and therefore decision-making thus risk being handled in an intuitive or arbitrary manner(Johnsen & Løkke, 2013).

The application from LCA results for policy makes it essential to interpret LCA results in a way that is decision supporting. Expressing LCA results in shadow costs is a first step that is helpful to relate the results to policy design.

Step 4) Interpretation of results

The interpretation step of LCA is essential to connect LCA results to policies. To connect LCA to policy the results should be robust and correctly interpreted. This research performs a contribution analysis to gain a deeper understanding why building's differ in environmental performance. When comparing types of buildings and electricity generation systems scenarios a contribution analysis will gain insight in what building's materials cause the difference in environmental impact.

LCA expert Simons mentioned the relevance of a contribution analysis of the LCA results (personal communication, 11 March 2020). Contribution analysis reviews LCA results by providing identification and comparison of the most contributing elementary flows (Beylot, Corrado, & Sala 2019). Consequently, the overview of major contributors provide a baseline to identify possible sustainable alternatives that could lead to a substantial reduction of the environmental impact. The contribution analysis is performed in this research and further described in the methodology.

2.2 Social acceptance of renewable energy innovations

Relevance of social acceptance

While many governments have ambitious renewable energy targets it is becoming increasingly clear that social acceptance may be a constraining factor to reach the targets (Wüstenhagen et al., 2007). Social acceptance as a part of renewable energy technology implementation has largely been neglected when policy programs started. Nevertheless, many of the barriers for achieving successful projects at the implementation level can be considered as a manifestation of lack of social acceptance (Wüstenhagen et al., 2007).

Furthermore, renewable energy has characteristics that could make social acceptance a constraining factor. Renewable electricity plans are smaller-scale compared to conventional power plants and are closer to the residents of electricity users which could cause negative noise and visual impacts. Additionally market acceptance could be hard when renewable energy innovations do not compete with incumbent technologies (Wüstenhagen et al., 2007).

The three dimensions of social acceptance

Social acceptance can be distinguished in three dimensions namely socio-political acceptance, community acceptance and market acceptance. These dimensions are shown in figure 2 below (Wüstenhagen et al., 2007).

Figure 2 ‘ the three dimensions of social acceptance’

For community acceptance the influence of procedural justice, distributional justice and trust are highlighted by the researchers (Flynn, Bellaby, & Ricci, 2011; Huijts, Midden, & Meijnders, 2007). Procedural justice encompasses whether there is a fair decision-making process giving all relevant stakeholders an opportunity to participate (Flynn et al., 2011). Distributional justice encompasses whether the costs and benefits in this process are distributed in a fair way (Huijts et al., 2007). Trust is whether the local community believes the information and intentions from investors and actors outside the community (Huijts et al., 2007).

Market acceptance refers to the process of adoption of the innovation and mainly depends on the acceptance of consumers and investors (Wüstenhagen et al., 2007). Rogers highlights the part regarding market acceptance from consumers. The characteristics of an innovation, as perceived by the members of a social system, determine its rate of adoption. Five attributes of innovations are relative advantage, compatibility, complexity, trialability and observability (Rogers, 2010).

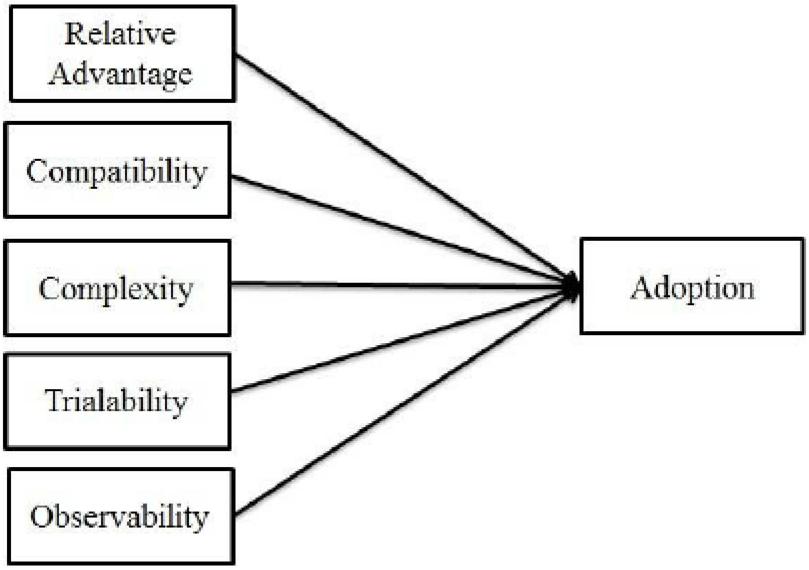

Figure 3 ‘The five attributes of innovation’ (Rogers, 2010)

A larger relative advantage, compatibility, trialability and observability as well as a lower complexity increases the speed of adoption (Rogers, 2010). This means that innovations will have a high adoption rate when these innovations have relative advantages over possible substitutes, low complexity, high trialability, observability and compatibility for the consumer.

Within the market acceptance of companies, intra-firm acceptance of renewable energy innovation plays a role (Wüstenhagen et al., 2007). Furthermore, market acceptance of companies is linked with socio-political acceptance, because these firms are influential stakeholders in the development of energy companies (Wüstenhagen et al., 2007).

Socio-political acceptance is regarding the generic acceptance of the technologies and policies by the public, key stakeholders and policy-makers (Wüstenhagen et al., 2007). The generic acceptance from renewable energy innovations by the community can differ from the acceptance of local projects (Wüstenhagen et al., 2007). For key stakeholders and policy actors a high level of socio-political acceptance requires institutionalization of frameworks that effectively foster and enhance market and community acceptance (Wüstenhagen et al., 2007).

2.3 Sustainable urban design

Sustainable urban design has a focus on design, planning, engineering, real estate and policy (Larco, 2016). In urban sustainable design literature, sustainable design possibilities are mainly focused on renewable and reduced energy supply, sustainable transportation and sustainable buildings (Keivani, 2010; Ritchie & Thomas, 2013; Larco, 2016). Ritchie and Thomas (2013) highlight that it is vital that we evolve towards sustainability in urban form, transport, landscape, buildings, energy supply, and all other aspects of vibrant city living. The framework from Larco (2016) for sustainable urban design takes into account energy usage and emissions of transportation, energy usage and emissions of buildings as the primary focus since these aspects have most impact on the environmental performance of an urban area. This research will only focus on the sustainable urban design of buildings.

Keivani (2010, p. 9) also highlights the need for a framework to support these goals and concludes: "Solutions require sociotechnical approaches at both macro and micro-levels encompassing innovative socio-technical solutions, institutional frameworks and shifting cultural attitudes for reducing energy consumption, encouraging renewable energy production, sustainable transportation options, and changing consumption patterns". Both Larco (2016) and Keivani (2010), note that policy and institutional frameworks are essential in sustainable urban design. Part 2.4 presents a developed conceptual model combining LCA and social acceptance of renewable innovations literature as tools for sustainable urban design policy.

2.4 Conceptual model policies for sustainable buildings

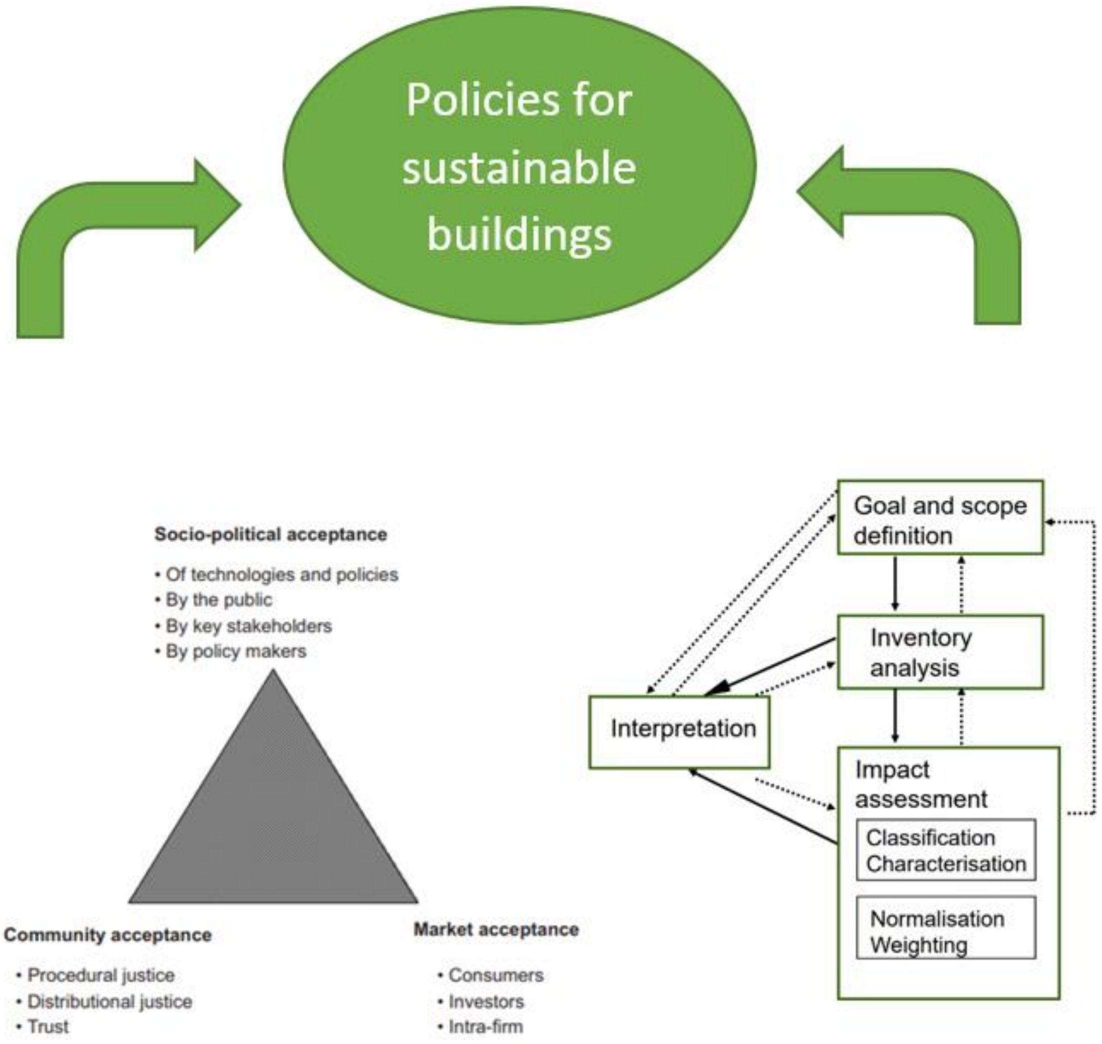

Figure 4 ‘conceptual model policies for sustainable buildings’

This conceptual model in figure 4 above connects policies for sustainable buildings to both social acceptance of renewable energy innovations and LCA methodology. The green arrows show that sustainable urban design policies in this research are analyzed from an environmental performance perspective by using LCA, as well as from a social acceptance perspective by using social acceptance of renewable energy innovations literature.

Both of them are relevant for sustainable urban design since the level of social acceptance has impact on the environmental performance since social acceptance determines both the adoption speed of transitions and whether transitions are implemented at all.

De Vries and Petersen (2009) argue for the importance of an integrated framework for sustainability assessments for sustainable urban design policy. They explain that the policy-making methodology should be a context-specific combination of formal, analytical methods and participatory methods (De Vries & Petersen, 2009). Combining LCA and social acceptance theory can be used to reach both goals since LCA focuses on analytical environmental performance assessment and social acceptance literature on the participatory factors.
This conceptual framework differs from the Vesta 4.0 model designed by the Netherlands Environmental Assessment Agency (PBL), which focuses on carbon dioxide emissions only (Van den Wijngaart, Van Polen, Van der Molen, Langeveld, & Van Bemmel, 2019). The Vesta 4.0 model is currently used to calculate the national scenarios for the heat transition in the urban environment (Van den Wijngaart et al. 2019). Using the LCA theory instead of the an analysis based on CO2 emission provides results based on multiple environmental impact categories.

This conceptual framework connects LCA methodology and social acceptance literature to policies for sustainable urban design. The methodology will explain how these concepts are operationalized. In order to make the LCA results interpretable, the literature on shadow costs and contribution analysis has been further elaborated.

3 Methodology

This chapter contains detailed description of the research design and operationalization(3.1), data collection and sampling(3.2), the data analysis(3.3), and the validity and reliability(3.4).

3.1 Research design and operationalization

Figure 5 shows the steps that were performed to answer the research question: ***How to relate LCA results of buildings to policies for sustainable urban design and how to design policies for sustainable buildings in The Netherlands?***

The boxes on the left represent the three parts in the results and the boxes on the right represent the different subtopics in those parts. The arrows indicate that the different parts in the results build upon each other and that in parts 2 and 3 the outcomes are used from the previous parts. That is to show that the procedure of interpretation of LCA results in part 1 has been applied in part 2 and the policy options in part 2 are the topic of the policy-making methodology in part 3.

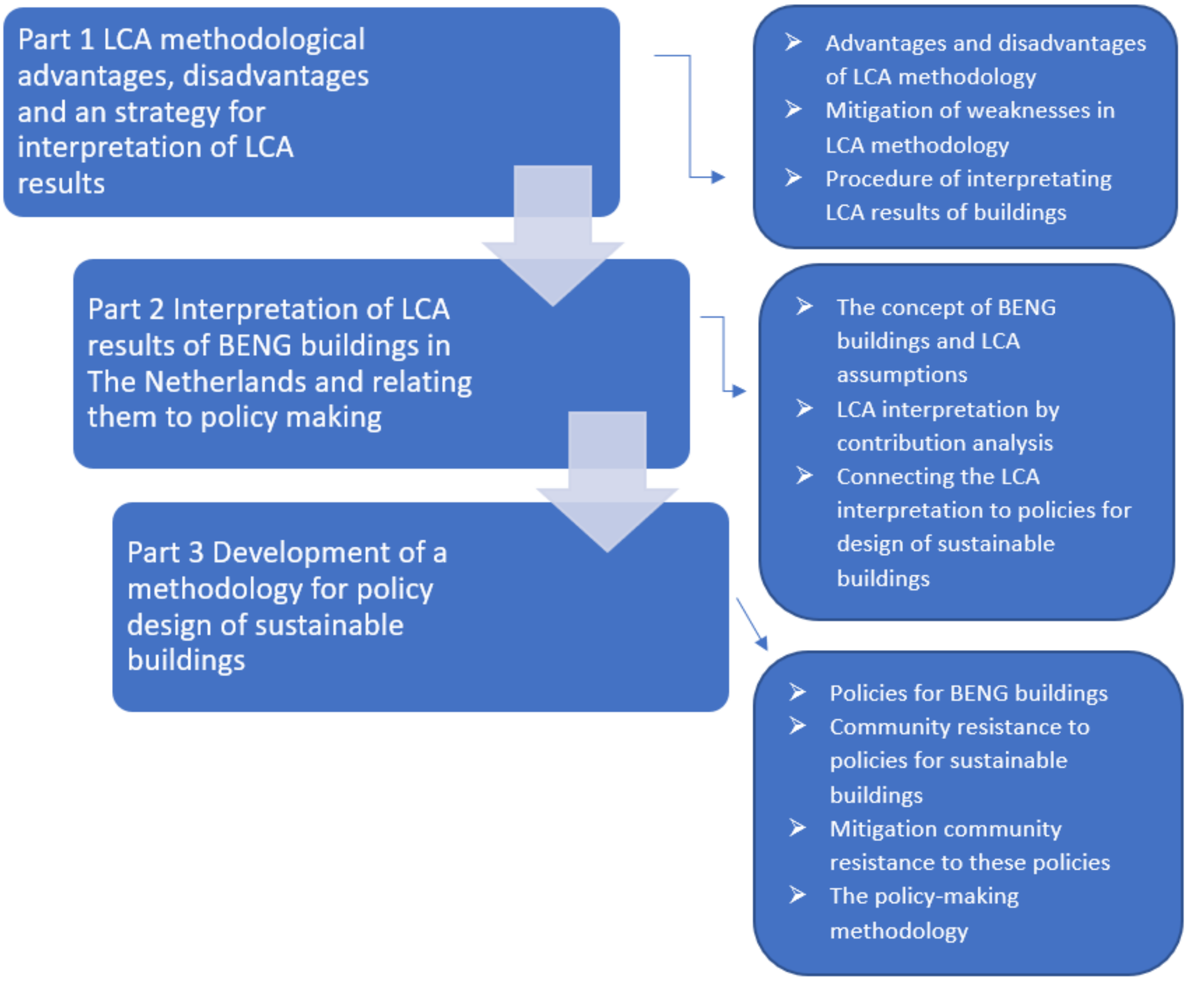

Figure 5 ‘Research design’

All steps in the research design as shown in figure 5 have been performed to answer the research question. First of all, interviews with LCA experts and literature research has been used in part 1 to describe the LCA methodological advantages, disadvantages and mitigation options as well as the procedure of interpretation of LCA results of buildings. Secondly, in part 2 the interpretation of LCA results from BENG buildings from W/E adviseurs (2019) are done by performing a contribution analysis and by interviewing an LCA expert regarding the underlying reasons for these LCA results. Thereafter, in part 3 the policy-making for sustainable buildings is described from the viewpoint of sustainable urban design experts, literature review and policy evaluation from the municipalities of Utrecht and Amsterdam who were guiding the transition to sustainable buildings. Finally, the policy-making methodology is developed based on the literature review which has been highlighted in the conceptual framework.

3.2 Data collection and sampling

The research used mixed methods and combined interviews with experts and literature review for data collection with both qualitative and quantitative analysis. Seven interviews with LCA and sustainable urban design experts were conducted from 60 to 90 minutes each and then transcribed and analysed. Purposive sampling and snowball sampling were used to select interview candidates with expertise regarding LCA and sustainable urban design. An overview of the interview candidates and my two company supervisors from LBP|SIGHT is given in the table 2 below.

Table 2 ‘Interview candidates and company supervisors’

Interview candidates and supervisors	Field of expertise	Company / University
Ric Hoefnagels	LCA	Utrecht University
Rene Kraaijenbrink	LCA	LBP|SIGHT
Paul van Vleuten	Sustainable urban design and sustainability	LBP|SIGHT
Erik de Jong	BENG buildings	LBP|SIGHT
Stephan Slingerland	Sustainable urban design and sustainability	Clingendael International Sustainability Centre Slingerland Policy Advice
Astrid Mangnus	Sustainable urban design and sustainability	Utrecht University
Martin Calisto	Sustainable urban design and sustainability	Utrecht University
Dirk-Jan Simons	LCA and sustainable urban design	LBP|SIGHT
Hilko van der Leij	LCA	LBP|SIGHT

The interviews were online on Skype and were semi-structured for the LCA experts and unstructured for the sustainable urban design experts. The interview candidates specialized in LCA were asked regarding the strengths and weaknesses, mitigation of weaknesses, the procedure, and interpretation step when applying LCA on buildings. The interviews regarding sustainable urban design covered social acceptance of sustainable transitions and mitigating options for low social acceptance.

3.3 Data analysis

This part covers the delineations and assumptions of the LCA study. The LCA interpretation step has been performed based on the LCA results on the building's materials of BENG buildings from W/E adviseurs (2019). First of all, the concept of BENG buildings will be defined. Secondly, the delineations of the LCA study will be given. Finally, the data operationalization of the LCA interpretation step is described.

The concept of BENG buildings

The Dutch government designed BENG buildings which stands for almost energy neutral buildings. The BENG buildings regulations are compulsory for all newbuild buildings from 2020 (Rijksdienst voor ondernemend Nederland, 2016). BENG buildings is a standard designed by the Dutch government which describes all building's materials of different buildings types for scenarios with all-electric, heat and gas electricity generation systems (Rijksdienst voor ondernemend Nederland, 2016). W/E adviseurs (2019) and LBP|SIGHT conducted an LCA on the BENG reference buildings of which the LCA interpretation has been done is this research. The LCA is conducted on the building's materials of BENG buildings and uses the materialization of these buildings described in the BENG standards as data for the inventory analysis. The LCA study was saved in an excel document designed by W/E adviseurs (2019) in cooperation with my internship company LBP|SIGHT. Their excel document with an inventory analysis and shadow costs calculations of BENG buildings has been used for further contribution analysis and interpretation in this research and is included as appendix.

Since BENG buildings are almost energy neutral buildings they are sustainable in the usage phase, due to its energy neutrality (Van der Leij, personal communication 02-10-2020). Nevertheless a drawback of the focus on energy neutrality is that the environmental impacts of building's materials like installations for PV panels and insulation materials can increase to accomplish almost energy neutral building's designs (Van der Leij, personal communication 2 October 2020). Therefore W/E adviseurs (2019) and LBP|SIGHT conducted an LCA on BENG building's materials comparing the all-electric, heat and gas scenarios. As BENG buildings are almost energy neutral the LCA results on the building's materials give a holistic view of which building types and electricity generation systems scenarios are most sustainable (Van der Leij, personal communication 2 October 2020).

LCA delineations

Three types of buildings are compared. A terraced building with sloping, a terraced building with a flat roof and a corner building with a sloping roof. The LCA of W/E adviseurs (2019) includes more building types, however these three building types are included in this research for the following two reasons. First of all, Statistics Netherlands (CBS) shows that 43% of the Dutch population lives in terraced and corner buildings and that these buildings types occur more frequently than all other building types (CBS, 2016). Secondly a comparison between these buildings has the potential to compare the sustainability impacts of roof design and of having adjacent buildings.

Three different electricity generation systems scenarios are compared for all buildings types namely the all-electric, heat and gas scenarios. The all-electric scenario is based on the usage of a heat pump. The heat scenario is based on external energy supply. The gas scenario is based on the usage of a boiler.

M^2 of gross floor area per year of a building is used as the functional unit in the LCA. This functional unit describes the function of the building which is providing living space for its inhabitants. By taking the gross floor area instead of the surface of the building only the useful floor area for living is taken into account.

The building's materials in the LCA comply with the Dutch standard for newbuild buildings designed by the government (Rijksdienst voor ondernemend Nederland, 2016). The LCA inventory is based on the obligated building's materials of BENG buildings regarding the number of PV panels (De Jong personal communication, 6 May 2020; Rijksdienst voor ondernemend Nederland, 2016). Furthermore expert in sustainable building and newbuild De Jong (personal communication, 6 May 2020) designed the inventory of the BENG buildings, which are based on a compliance with the BENG regulations and his expertise on newbuild buildings.

The system boundaries are all building's materials and installations for heating the building. A lifetime period of 75 years is assumed for the buildings (W/E adviseurs, 2019). Additionally, system boundaries are compliance with the following two BENG regulations. First of all, the energy requirement and primary energy consumption of the buildings do not exceed 25 kWh / m2 floor area / year. Secondly, the share of renewable energy for building related energy usage is at least 50% (Rijksdienst voor ondernemend Nederland, 2016).

The LCA results were expressed in shadow costs, and the impact assessment step has been performed by certified LCA expert Jeannete Levels (De Jong personal communication, 6 May 2020). The Dutch National Environmental Database (NMD version 3.0) is used for the impact assessment in combination with the "SKB bepalingsmethode" version 3.0 from the Dutch Quality Building Foundation which is used for the weighting step (W/E adviseurs, 2019). Both the "NMD version 3.0" and "SKB bepalingsmethode version 3.0" were released in 2019 and are standards for LCA analysis in the Netherlands (Nationale Milieu Database, 2019).

Contribution analysis

This research performed a contribution analysis on the LCA results from W/E adviseurs (2019), comparing the buildings types terraced buildings with a sloping and flat roof and corner buildings for scenarios with all-electric, heat and gas electricity generation systems. The contribution analysis includes the impact of four categories namely, foundation, floors, roofs & facades, installations. The contribution analysis compares the shadow costs for the three buildings types with the all-electric, heat and gas scenarios for each of these four categories. Furthermore, a contribution analysis has been performed to calculate how much the shadow costs from PV panels contribute to the differences in shadow costs between the all-electric, heat and gas scenarios. This analysis has been done by dividing the differences in shadow costs of PV panels between the all-electric, heat and gas scenarios by the total difference in shadow costs between the all-electric, heat and gas scenarios. The contribution analysis was performed in excel and the results were visualised in charts. The calculations of the contribution analysis are included in the appendix.

Consequently an interview with an LCA expert and literature research is done on the underlying technical reasons why and how BENG buildings differ in their environmental performance by its building type and electricity generation system. The LCA has been related to policy-making in two different ways. First of all, the LCA interpretation is related to policies for BENG buildings by recommending the most sustainable building types and electricity generation systems. Secondly, the LCA interpretation is related to existing buildings which do not comply with the BENG regulations, since the LCA interpretation supports the Dutch governmental policy of the natural-gas free transitions for 7.7 million households. Consequently, the social acceptance of the natural-gas free transitions has been analyzed based on interviews with sustainable urban design and policy experts. The focus is on the natural-gas free transition and the disadvantages and advantages of current governmental policies, and mitigation possibilities to improve policy design is described and supported with policy evaluation from the municipalities of Utrecht and Amsterdam and literature research.

3.4 Validity and reliability

Data triangulation is used, which means different sources are combined to get richer, fuller data and increase the validity by confirmation of the results by different sources (Flick, 2002). To improve the reliability of the results, an interview with sustainable building and newbuild expert De Jong was held to verify the reliability and improve the interpretation of the LCA study of W/E adviseurs (2019). Furthermore, to increase the validity and reliability, multiple data sources are used to combine insights from different perspectives. An aspect that decreases the validity of the results it the use of shadow costs, because the weighting step is controversial since it is not an exact science (Eldh & Johansson, 2006). Nevertheless this step was necessary to relate the LCA results to policies since without weighting, decision-making risk being handled in an intuitive or arbitrary manner (Johnsen & Løkke, 2013).

The research design was an appropriate method to answer the research question since the expertise of LCA experts was essential to interpret the LCA data and relate them to policy. Furthermore the expertise of sustainable urban design experts was essential to describe the constraining factors and mitigation possibilities from policies for sustainable buildings in the Netherlands. The inclusion of literature review and the policy evaluation ensured the quality of data from the interviewed experts and increased the validity of the research.

4 Results

The results section answers the research question: ***How to relate LCA results of BENG buildings to policies for sustainable urban design and how to subsequently develop policies for sustainable buildings in the Netherlands?***

The results are divided into three main parts. Firstly, the LCA methodological advantages and disadvantages, and a strategy of interpretation of LCA results (4.1) is covered. Secondly, the LCA interpretation is done and related to policies for sustainable design of buildings (4.2). Finally, the third part covers policy recommendations for BENG buildings, policy evaluation for the natural-gas free transition and the policy-making methodology for sustainable buildings (4.3).

4.1 LCA methodological advantages and disadvantages, and a strategy of interpretation of LCA results

This part discusses the LCA methodological advantages and disadvantages, mitigation possibilities of weaknesses and strategy to apply LCA on buildings.

Advantages of applying LCA

Both methodological advantages and disadvantages are mentioned by experts regarding applying LCA for sustainable urban design. Hoefnagels mentions (personal communication, 30 April 2020) : "LCA results are very useful for sustainable urban design. The main strength of the methodology is the life cycle principle. By applying LCA, the results account for environmental impacts of raw material acquisition, production, use, and disposal, even when these processes take place in other locations. Consequently applying LCA for sustainable urban design contributes to detailed knowledge of the environmental performance, that can be applied in sustainable urban design (Hoefnagels personal communication, 30 April 2020).

Furthermore, applying LCA has the advantage that it provides a baseline for comparing multiple urban design scenarios based on environmental performance. This offers an incentive for sustainable transitions and a baseline for objective comparison for sustainable urban design. Earlier research shows that LCA is indeed a decision supporting tool for sustainable urban design (Den Boer, Den Boer, & Jager, 2007).

Summarizing the main advantages of LCA for sustainable urban design are first of all that the environmental performance can be assessed while taking into account all product-life stages. Secondly, LCA can offer incentives for sustainable transitions and comparison of environmental performance in different scenarios. Thirdly, LCA can be a decision supporting tool for sustainable urban design.

Disadvantages of applying LCA and possibilities to mitigate weaknesses

LCA experts Hoefnagels (personal communication, 30 April 2020) and Kraaijenbrink (personal communication, 4 May 2020) both agree that poor assessment of regional environmental impacts is a weakness in the LCA methodology. According to Hoefnagels (personal communication, 30 April 2020): "In LCA methodology, all impacts from the product life cycle are added, which results in a loss of the geographical location of the impacts. However, mid-point indicators in LCA like nitrogen or sulfur emissions do have different environmental impacts depending on the local environment. For example, nitrogen and sulfur can both cause soil acidification in nature, resulting in a loss of biodiversity. Therefore, the environmental impacts of nitrogen or sulfur can heavily depend on the geographical location of the emissions" (Hoefnagels personal communication, 30 April 2020).

The topic of local nitrogen emissions has recently gained a lot of attention in Dutch media and politics. Since the Dutch government has made new nitrogen legislations in December 2019, farmers and construction workers organized large protests against this decision (NOS, 2019). Farmers, construction workers, and media expressed concerns regarding having to end work projects since they are unable to comply with the nitrogen legislation. To conclude, the local impact of some emissions such as nitrogen and sulfur have a key role in sustainable urban design and are not properly assessed in LCA methodology.

Other research confirms the methodological LCA weakness mentioned by Hoefnagels (personal communication, 30 April 2020) and Kraaijenbrink (personal communication, 4 May 2020), suggesting different mitigation strategies are needed. Hiloidhari et al. (2017) conclude that current LCA measures are inadequate to account for spatial aspects. To mitigate these effects, integrating GIS and LCA could address such issues by allocating the impacts into spatial units (Bengtsson et al., 1998; Geyer et al., 2010; Gasol et al., 2011). This methodology called spatial LCA[3] makes it possible to analyze the local impacts in LCA results.

Several researchers (Curran et al., 2011; De Souza et al., 2015) support the statement from Hoefnagels that it is problematic to assess biodiversity impacts with LCA. “Incorporating impacts on biodiversity in life cycle impact assessment is challenging. The vast majority of LCA approaches look at biodiversity impacts by land-use and land-use change only” (Hoefnagels personal communication, 30 April 2020). Ahmed, Van Bodegom, and Tukker (2019) argue that functional diversity provides a more generic tool to assess environmental impacts on biodiversity in LCA. The functional diversity metrics is a methodology to measure the human impacts on the richness, evenness, and diversity of species.

Another disadvantage of applying LCA for sustainable design is that the LCA methodology does not provide a holistic viewpoint for sustainable urban design. “LCA can only be one of the tools, however not the tool” (Hoefnagels personal communication, 30 April 2020). For example, quantitative environmental performance results from different urban designs, do not describe the population’s opinions regarding these different urban design options (Hoefnagels personal communication, 30 April 2020). So, using LCA as the only tool would be problematic since it is not a holistic tool for sustainable urban design.

By interpretation of Hoefnagel’s statements he suggests: “relating environmental performance assessment to economic, social and political dimensions is a key aspect of sustainable design (Hoefnagels personal communication, 30 April 2020)”. An example from an interview with sustainable urban design and environmental governance expert Calisto makes clear that: “There is no sustainable neighborhood if nobody wants to live in it. In China, they built these crazy sustainable cities, completely new from the ground but no one lives in them and no one is there” (Calisto personal communication, 20 May 2020). These examples show economic, social and political dimensions cannot be neglected to reach sustainable urban design.

To summarize the main weaknesses of LCA for sustainable urban design in terms of environmental assessment are the poor assessment of local impacts and biodiversity. Literature suggests using spatial-LCA and the functional diversity metrics as possible mitigation options.

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[3] Spatial-LCA is the integrated use of GIS and LCA (Hiloidhari et al., 2017)

Strategy to apply LCA on buildings

The LCA experts were asked what principles are key in applying LCA on buildings, which is the focus of this research. Buildings are a significant contributor to environmental impacts on an urban scale since 32% of the total final energy consumption in the Netherlands is for heating purposes. Furthermore sustainable design of buildings has an interlinkage with the sustainable urban design when electricity generation or energy generation which is done for heating buildings takes place in a different location. Hoefnagels mentioned: “LCA is a good methodology to use for sustainable urban design of buildings, once it is related to clear sustainable urban design goals.

From Kraaijenbrink’s interview can be interpreted that gathering and analyzing existing LCA data of buildings is more effective than generating LCA data. Kraaijenbrink mentioned: “For relating LCA data analysis on buildings to policy-making, the main challenge is to gather and analyze the available data. It is pointless to generate LCA data by yourself” (Kraaijenbrink personal communication, 4 May 2020). The reasoning behind this is that Kraaijenbrink (personal communication, 4 May 2020) argues that for policy-making it is more efficient to interpretate LCA results.

This part summarizes the experts’ recommendations regarding applying LCA on buildings for sustainable design. First of all, LCA methodology should be combined with other tools since LCA methodology alone does not provide enough basis for decision making. Secondly, there needs to be a clear connection to a sustainable urban design goal in the LCA analysis.

4.2 LCA interpretation and the relation to policies for sustainable design of buildings

In this part the LCA interpretations step is performed based on the LCA results on the building’s materials of BENG buildings from W/E adviseurs (2019). First of all, an overview of the LCA results from W/E adiviseurs(2019) is presented. Secondly, the contribution analysis is performed. Thirdly, the underlying technical reasons why and how BENG buildings differ in their environmental performance by its building type and electricity generation system is described based on personal communication with LCA expert Van der Leij and literature review.

LCA on building’s materials overview of results

This parts includes an overview of the LCA results on the building’s materials of BENG buildings (W/E adviseurs, 2019). The LCA interpretation compares the environmental impacts of the BENG building’s materials from terraced buildings with a sloping roof, terraced buildings with a flat roof and corner buildings for scenarios with all-electric, heat and gas electricity generation systems. The annual shadow costs are given in euros per m^2 of gross floor area in all charts. Chart 1 shows the total annual shadow costs for the three building types with different electricity generation system scenarios. Furthermore the relative percentual impact of the all-electric, heat and gas scenarios are compared in Chart 2.

Chart 1 ‘ Total annual shadow costs of BENG building’s materials’

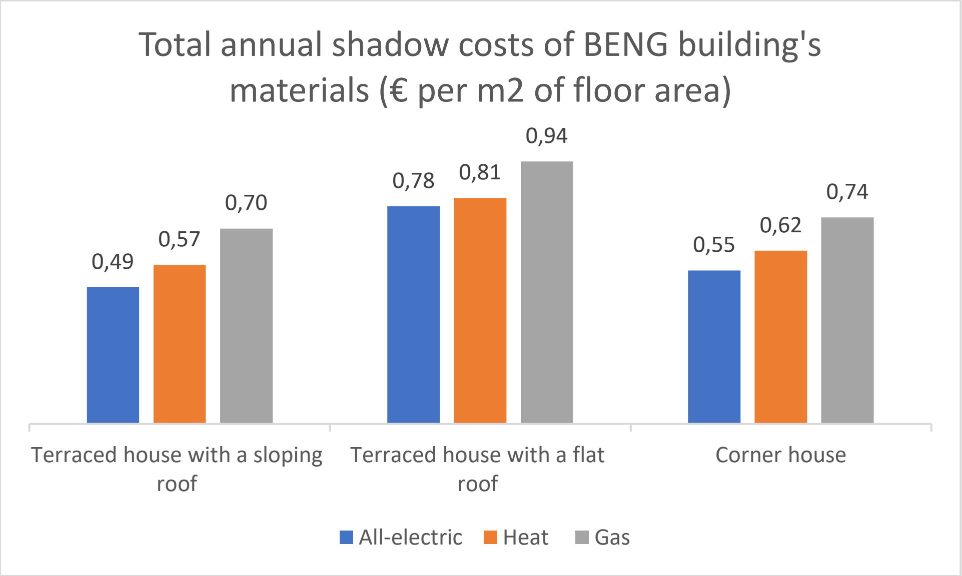


Chart 1 shows for all-buildings types the shadow costs are lowest for the all-electric scenario and highest for the gas scenario. The heat scenario shows for all buildings types higher shadow costs compared to the all-electric scenario and lower shadow costs compared to the gas scenario. Furthermore the terraced buildings with a flat roof shows higher shadow costs than the other buildings. Chart 1 suggest that having a sloping roof design and more adjacent buildings increases the sustainability. This is suggested, because when comparing the sloping roof design versus the flat roof design the terraced building with a sloping roof has lower shadow costs than the terraced building with a flat roof. Furthermore, when comparing the number of adjacent buildings the terraced building with a sloping roof has lower shadow costs compared to the corner building. The sustainability impacts on roof design and the number of adjacent buildings are only suggested and not proven since other differences between the buildings could also influence the shadow costs.

Chart 2 ‘Percentual impact of electricity generation scenarios’

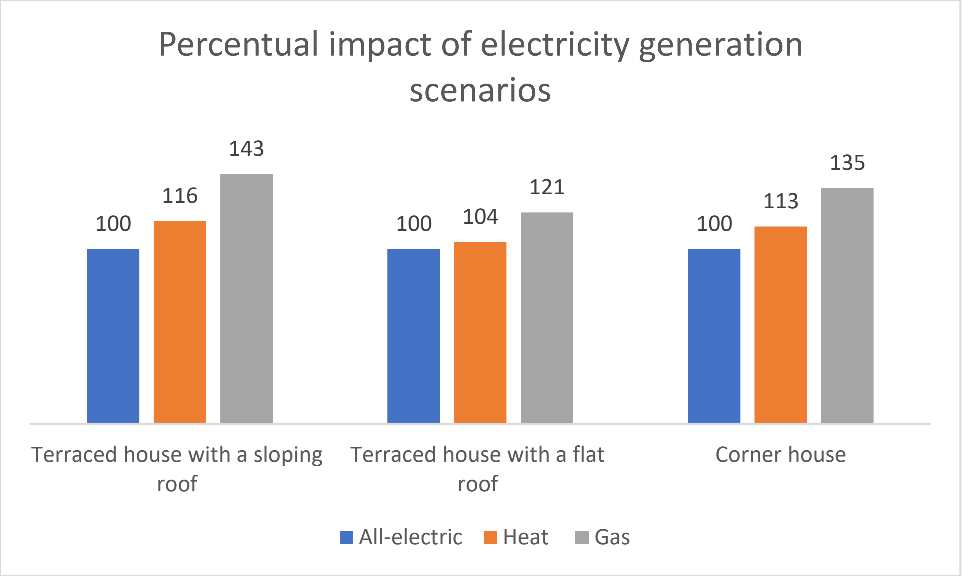


Chart 2 shows the percentual difference between the all-electric, heat and gas scenarios given in chart 1. The all-electric buildings are used as a reference and have been assigned a 100% score. The gas scenario has 21% to 43% larger impact than the all-electric scenario, depending on the building type. The heat scenario has 4% to 16% larger impact than the all-electric scenario, depending on the building type. The percentual impact between the all-electric, heat and gas scenarios differs less in the terraced building with a flat roof compared to the other buildings.

LCA contribution analysis

A contribution analysis is performed on the building's materials of the BENG buildings. The shadow costs of all-electric, heat and gas scenarios are compared for the four categories, foundation, floors, roofs & facades and installations. The foundation includes the impacts of all walls, beams and posts. The floors include the concrete, tiles and insulation materials. The roofs & facades include cavity walls, glazing, concrete, wood and insulation materials. The installations include electricity generation systems, heat distribution systems, heat generation systems as well as pipes for electricity, air and water distribution.

In charts 3,4 and 5 the annual shadow costs of electricity generation systems scenarios are compared on the subcategories foundation, floors, roofs and facades, and installations for the three building types.

Chart 3 'Contribution analysis terraced building with a sloping roof '

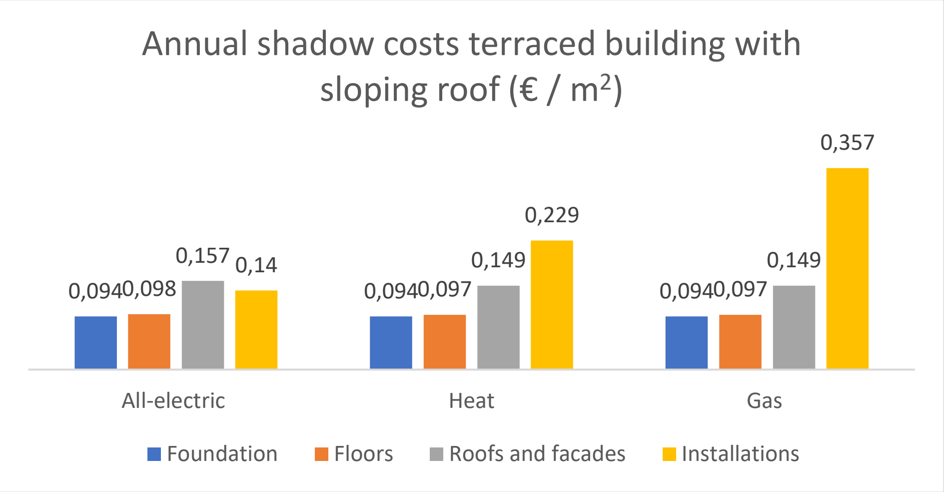


Chart 4 'Contribution analysis terraced building with a flat roof '

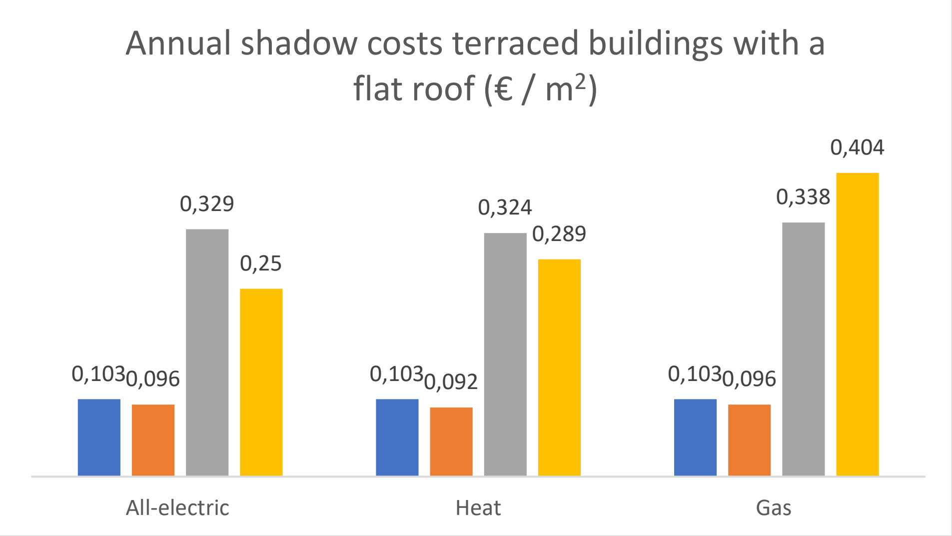
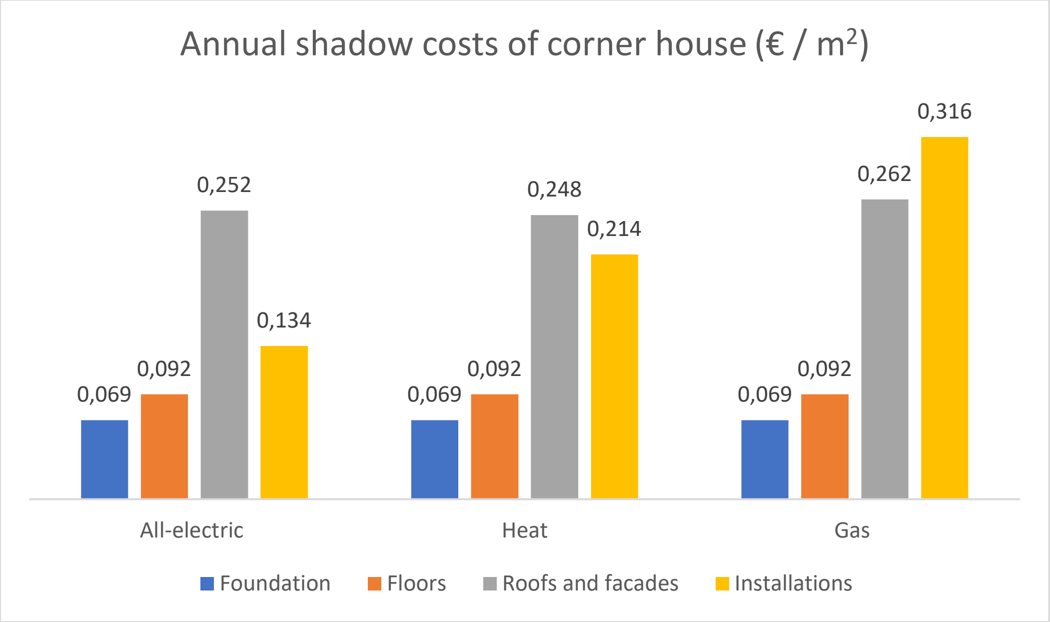


Chart 5 ‘Contribution analysis of a corner building with a sloping roof ’



How do LCA results differ regarding the choice of the all-electric, heat and gas scenarios?
The shadow costs of foundation is similar for the all-electric, heat and gas scenarios regardless of the building type. The shadow costs of floors and roofs & facades is almost the same for the all-electric, heat and gas scenarios, regardless of the buildings type. The only difference for the impact of roofs & facades is that the all-electric scenario for some buildings types has a larger amount of insulation materials. The shadow costs of installations differs significantly between the all-electric, heat and gas scenarios for all the three building types.

Charts 3,4 and 5 show for all-buildings types the shadow costs of installations are lowest for the all-electric scenario and highest for the gas scenario. The heat scenario shows for all buildings types higher shadow costs for installations compared to the all-electric scenario and lower shadow costs compared to the gas scenario.

How do results differ regarding the choice of building type?
Furthermore Charts 3,4 and 5 show that shadow costs of roofs and facades are lowest for the terraced building with a sloping roof. The building designs with a flat roof shows the highest shadow costs for roofs and facades.

Contribution analyses of PV panels
The previous part shows that the shadow costs of installations differ between the all-electric, heat and gas scenarios. The LCA inventory data show that the impact of installations differ particularly because of the shadow costs contribution of PV panels.

Therefore another contribution analysis on PV panels is performed. This contribution analysis aims to find out the contribution of PV panels to the differences in shadow costs between all-electric, heat and gas scenarios. Chart 6 shows BENG buildings differ in the number of PV panels for all-electric, heat and gas buildings.

Chart 6 ‘PV panels of BENG buildings’

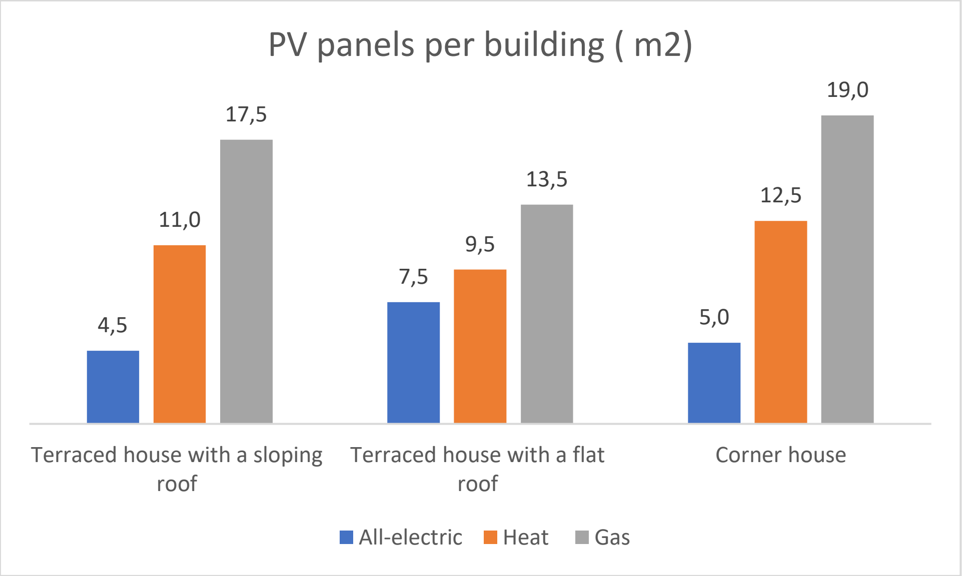


Chart 6 shows for all-buildings types the number of PV panels are lowest for the all-electric scenario and highest for the gas scenario. The heat scenario shows for all buildings types a larger number of PV panels compared to the all-electric scenario and a lower number of PV panels compared to the gas scenario.

Chart 7 ‘Shadow costs from PV panels’

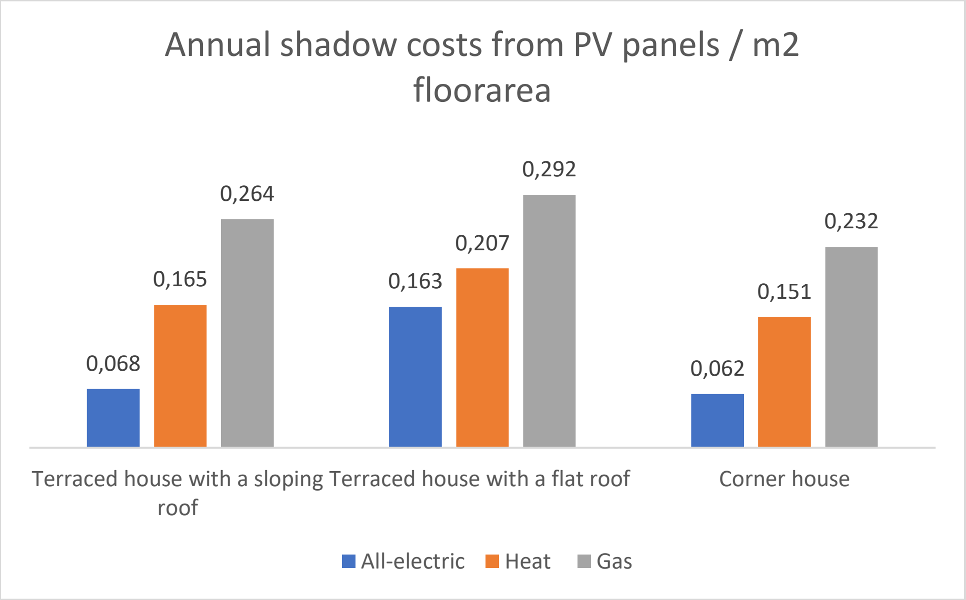
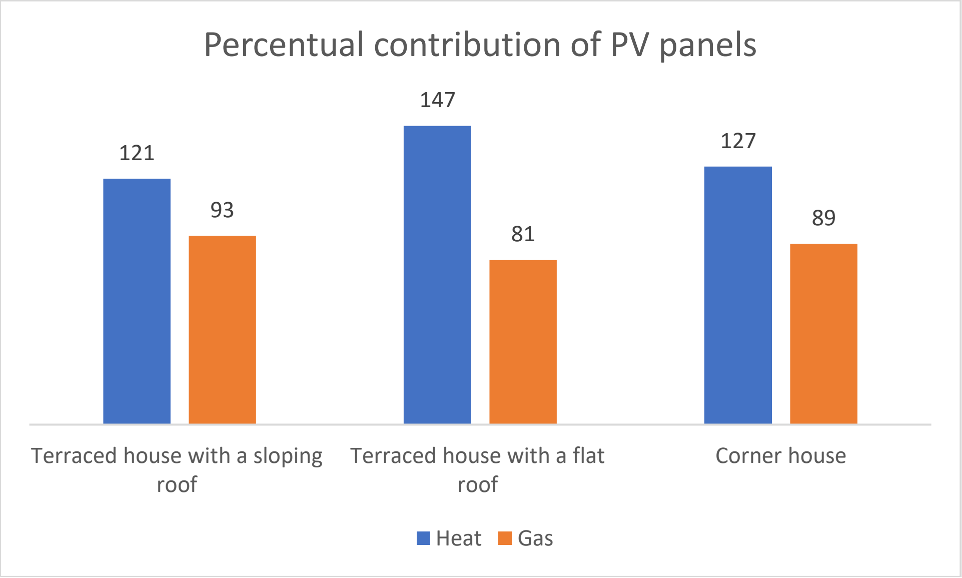


Chart 7 shows the shadow costs by the PV panels. Chart 8 shows the percentual contribution of PV panels to the differences in the building’s material shadow costs given in Chart 1. As shown in Chart 1 the all-electric scenario has the lowest shadow costs. Therefore for the heat and gas scenarios Chart 8 shows how much of the additional shadow costs the heat and gas scenarios have compared to the all-electric scenario is caused by shadow cost from the larger number of PV panels.

Chart 8 ‘ Contribution analysis of PV panels’



The data in Chart 8 are calculated by dividing the difference in shadow costs by PV panels in Chart 7 by the total difference in shadow costs between the all-electric, heat and gas scenarios in Chart 1. The following formula is used and the appendix describes the details of this calculation.

$$Percentual\ contribution\ of\ PV\ panels = \frac{additional\ shadow\ costs\ by\ PV}{additional\ shadow\ costs} \times 100\%$$

For the heat scenario the percentual contribution caused by PV panels to the shadow costs difference between heat and all-electric buildings ranges from 121% to 147%. This means that the shadow costs of the heat buildings, regardless of the building type, would be lower compared to the all-electric buildings in case both buildings would have the same number of PV panels. For the gas scenario the percentual contribution caused by PV panels to the shadow costs difference between gas and all-electric buildings ranges from 81% to 93%.

Technological reasons for difference in number of PV panels

The reason for differences in the number of PV panels is caused by technological differences between the electricity generation systems (Van der Leij, personal communication 2 October 2020). The main technological difference is that the all-electric scenario with the use of heat pumps can reach much higher efficiencies compared to a boiler for gas (Van der Leij, personal communication 2 October 2020). Visser (2014) confirms this and estimates a heat pump has a coefficient of performance of 4 which corresponds with a 400 percent efficiency. A heat pump can reach efficiencies above 100 percent by transferring heat instead of generating heat. Conventional natural gas boilers have an efficiency of 70% to 80% (Qu, Abdelaziz, & Yin, 2014).

These energy efficiency differences between the heat pump and the natural gas boiler technologies cause the difference in number of PV panels shown in Chart 6 (Van der Leij, personal communication 2 October 2020). As the heat pump technology is more efficient a smaller number of PV panels is needed in the all-electric scenario to accomplish energy-neutrality and comply with the BENG regulations compared to the gas scenario.

LCA interpretation and policies for sustainable buildings

One of the research goals is to relate the LCA interpretation of BENG buildings to policies for sustainable buildings in the Netherlands. Two policy options for sustainable design of buildings in existing buildings—which are in line with the LCA interpretation finding that the gas scenario is the least sustainable—are already implemented by the Dutch government and supported by sustainable urban design expert Slingerland (personal communication, 22 May 2020). These policy options towards natural-gas free buildings are the transition to the heat scenario or the all-electric scenario (Rijksdienst voor ondernemend Nederland, n.d.). For existing buildings the transition to the heat scenario is an implementation of central city heating systems and the all-electric scenario is implementation of heat pumps in buildings (Rijksdienst voor ondernemend Nederland, n.d.).

The all-electric, heat and gas scenarios differ in potential to further increase the sustainability by increasing the usage of renewable energy sources for non-building related energy usage. For the all-electric scenario, electric demand can be supplied from PV panels or regional wind turbines (Van Leeuwen, Van Wit, & Smit 2017). For the heat scenario the possibilities of a central heating system are to use renewable energy sources from waste, biomass, bio-fuel conversion, solar thermal plants, power to heat, shallow and deep geothermal energy, and seasonal thermal storage (Olsen et al., 2008). For the gas scenario, an possibility for sustainable gas usage is heating buildings in the Netherlands by purification of bio-gas into methane, which makes it possible to inject it into the gas grid (Van Leeuwen et al., 2017). A disadvantage of the gas scenario is that the technology to integrate biogas into the existing gas infrastructure is a costly (Ryckebosch, Drouillon, & Vervaeren, 2011; Wellinger, Murphy, & Baxter, 2013). To summarize the heat scenario has the most potential to further improve the sustainability by increasing the usage of renewable energy sources—whereas the gas scenario has almost no feasible option to further improve the sustainability with increased usage of renewable energy sources—and the all-electric scenario has less potential compared to the heat scenario, but more potential compared to the gas scenario.

The LCA interpretation shows that BENG buildings with the gas scenario have a larger environmental impact. Furthermore buildings with the gas scenario need a significant larger share of PV panels to comply with BENG regulations. This suggests that a transition from the gas buildings with to all-electric or heat buildings seems essential. Sustainability policy expert Slingerland confirms this and mentioned: “The two main policy options for the transition are from buildings with gas electricity generation systems to either buildings with an all-electric electricity generation systems or to buildings with an heat electricity generation systems. It depends on the city or neighborhood which of these options is favorable, since the potential of a central city heating systems for the heat scenario differ per location” (Slingerland personal communication, 20 May 2020).

The Dutch governmental policy supports the natural-gas free transition and mentioned: “From 2021 annually 50.000 buildings need to stop using gas electricity generation systems and by 2030 this number needs to be increased to 200.000” (Rijksdienst voor ondernemend Nederland, n.d. p.14). Schoots en Hamming (2019) confirm that natural gas has high environmental impact by stating: “about 36% of the Dutch energy is used in the urban environment of which natural gas is a big part. The natural-gas free transition in The Netherland as suggested by the governmental policy is of a substantial size and should take place in 7 million Dutch buildings and 1 million other buildings (Scholte et al., 2020 p.5) “. The research from Scholte et al. (2020) also confirms the statement from Slingerland that: “a neighborhood oriented approach is key in this transition since it depends on the location whether industry residual heat or local geothermal energy is available (Slingerland personal communication, 22 May 2020).

Summarizing both the LCA interpretation and other researchers, highlights the need for transitions in the Netherland from gas to all-electric or heat electricity generation systems and to increased use of renewable energy sources in buildings (Scholte et al, 2020 ; Slingerland personal communication, 22 May 2020). The natural-gas free transition besides improving the environmental performance also improves the potential to further increase the usage of renewable energy sources in buildings for non-building related energy usage (Van Leeuwen, et al. 2017).

4.3 Policy recommendations for BENG buildings, policy evaluation for the natural-gas free transition and the policy-making methodology for sustainable buildings

This part contains a detailed description of policy recommendation for BENG buildings, policy evaluation for the natural-gas free transition and the policy-making methodology for sustainable buildings.

Policies recommendations for BENG buildings in the Netherlands

Policy-makers are recommended to select the most sustainable BENG buildings. The LCA interpretation provides insight for policy makers regarding the level of sustainability of BENG buildings. Questions regarding which types of BENG buildings should be preferred are answered below based on the LCA interpretation.

What is the most sustainable electricity generation system of BENG buildings?

The LCA interpretation shows in chart 1 that for BENG buildings that the all-electric scenario is the most sustainable for all building types. Due to the BENG buildings energy-neutrality the buildings are sustainable in the use phase. Therefore, the LCA interpretation of the analysis on BENG building's materials suffices to conclude what scenario of electricity generation system is most sustainable. The gas scenario is the least sustainable and the heat scenario is more sustainable than the gas scenario, however less sustainable than the all-electric scenario.

What causes these differences in environmental performance of the BENG building's materials between the scenarios of electricity generations systems?

The contribution analysis shows that the environmental impacts from installations, particularly from PV panels causes these results. The environmental impacts from the foundation, floors, roofs and facades are almost similar across the all-electric, heat and gas buildings types. Chart 8 shows that 81% to 147% of the difference in environmental impact between the all-electric, heat and gas scenarios can be explained by the differences in number of PV panels.

Why do all-electric, heat and gas BENG buildings differ in number of PV panels?

This is for technological reasons since the efficiency of heat pumps in the all-electric scenario can reach up to 400%, whereas for a gas boiler has a typical efficiency of 70 to 80% (Visser, 2014; Qu et al., 2014 ; Van der Leij, personal communication 2 October 2020). Consequently, a larger number of PV panels is needed for gas buildings to comply with the BENG regulations compared to all-electric buildings.

Is a sloping or a flat roof design more sustainable?

Chart 1 suggest that a sloping roof design is more sustainable since the terraced building with a flat roof has higher shadow costs compared to the terraced building with a sloping roof. Nevertheless terraced buildings with a flat and sloping roof also differ in their gross floor area. Therefore this research does not confirm a causal correlation that proves that sloping roof designs are more sustainable than flat roofs.

Can the results of BENG buildings support the natural-gas free transition for existing buildings?

The technological reason for why the all-electric scenario is more sustainable than the gas scenario is also valid for existing buildings which do not comply with BENG regulations. Therefore the LCA interpretation supports the Dutch governmental policy of a natural-gas free transition in buildings. Consequently a policy evaluation has been done on the natural-gas free transition.

Policy evaluation for the natural-gas free transition in Dutch buildings

The LCA interpretation, Dutch governmental policy and experts showed for sustainable design of buildings a natural-gas free transition in The Netherland is needed, which can either be done by the transition to the all-electric scenario or to the heat scenario. Nevertheless, the interview with policy expert Mangnus shows that implementing the natural-gas free transition in Dutch buildings and designing the appropriate policies is challenging. Mangnus mentioned: “the knowledge-action gap for these transitions is big. A lot of people know what sustainable transitions are possible, however, the actual speed of transitions is still low (Mangnus, personal communication, 22 May 2020). Furthermore, the natural gas-free transition in buildings which is ongoing in The Netherlands encounters the problem of community resistance (Mangnus, personal communication, 22 May 2020). Policy expert Mangnus mentioned: “In Utrecht Overvecht an ambitious plan was made to make the entire neighborhood natural gas-free. This was an emotional issue for inhabitants and due to public resistance, these plans have been postponed” (Mangnus, personal communication, 22 May 2020). Policy expert Mangnus (personal communication, 22 May 2020) shared her thoughts on why this transition was so difficult: “Sustainable urban design usually happens in projects from construction companies. For construction companies it is simple to make big changes for an entire neighborhood, however the local inhabitants are scared when they are forced to change. I saw even people cooking at home with a camping gas stove because they were so emotionally related to cooking with gas. It is clear that these events are undesirable in the transitions process, and the governmental policies can impact the way transitions take place.”

The Dutch government has selected 27 neighborhoods to make the transitions to natural gas-free living (Mangnus, personal communication, 22 May 2020). Evaluations of the transition process from Utrecht Overvecht and other neighborhoods are published by the government and local municipalities. (Rijksdienst voor ondernemend Nederland, 2019 ; Rijksdienst voor ondernemend Nederland. n.d.)

In the reflection report regarding the natural gas-free transition, the following problems have been mentioned by the municipality of Utrecht. First of all, the municipality noticed a low community acceptance of the transition. Secondly, also stakeholders and energy suppliers have lack of incentive and no legal obligation to participate. Thirdly, the municipality found it challenging to guarantee the public interest (Rijksdienst voor ondernemend Nederland, 2019). The reflection report highlights the low level of community acceptance with the following statements. “ It is a non-achievable goal that all residents of Overvecht agree with the natural gas-free transition. For the municipality, it stays a dilemma what the best way is to guide the residents in this transition”(Rijksdienst voor ondernemend Nederland, 2019, p. 3).

The reflection report also highlights that the driving efforts to implement the natural gas-free transition only come from the municipality. “The municipality is the driving force behind this transition. All other parties participate in the transition voluntarily. The power from the municipality would be larger when there would be different laws or national policies. The other participants in the transition have different aims than the municipality “ (Rijksdienst voor ondernemend Nederland, 2019, pp. 2-3).

The reflection report highlights that it is challenging for the municipality to guarantee public interest.“ The municipality mentions in cooperation with companies it is hard to guarantee the public interest. It is unclear what business case the companies have and this is important for the affordability of the residents. “ (Rijksdienst voor ondernemend Nederland, 2019, p. 3).

To summarize both sustainable urban design expert Mangnus and the municipalities of Utrecht and Amsterdam highlighted that low community acceptance is a constraining factor for the implementation of the natural-gas free transition in buildings (Mangnus personal communication, 22 May 2020 ; Rijksdienst voor ondernemend Nederland, 2019).

The previous research findings pose two main questions for policy namely, how to possibly mitigate low community acceptance and whether the transition towards the all-electric or the heat scenario should be chosen. Regarding the issue of mitigation of low community acceptance, the research institute DRIFT published a research on natural-gas free neighbourhoods in the Netherlands and the impact of governance, in which mitigation options for community resistance are suggested (Beers, Oxenaar & Notermans, 2019). Changing the guiding role of municipalities to a more supporting role by giving a more influential role to local residents could avoid the problem of low community acceptance (Beers et al., 2019).

Regarding the policy options for a natural-gas free transition the previous research findings shows either the transition with the all-electric scenario or the transition with the heat scenario should be chosen. Since both the all-electric and heat scenarios are suggested alternatives for the gas scenario literature review is done on advantages and disadvantages of both. Currently, the gas scenario is the dominant heating system in the Netherlands (Van Leeuwen et al., 2017). Differences between the all-electric and the heat scenario are that, the transition to the all-electric scenario is possible on an individual scale whereas the transition to the heat scenario has to be implemented on a collective scale (Van Leeuwen et al., 2017). In the transition to the all-electric scenario the building's natural gas boiler can be replaced by a heat pump to switch to the all-electric scenario. This approach is possible on an individual scale since it can be implemented for a single building. In the transition to the heat scenario buildings are connected to a central city heating system. This district heating approach can only be implemented on a collective scale.

The collective approach of the heating scenario has advantages for the integration of renewable energy, especially for existing buildings in densely populated areas (Lund, Möller, Mathiesen, & Dyrelund, 2010). Nevertheless, new low-energy buildings require less energy for space heating which makes individual heating systems more attractive compared to the collective approach. An advantage of the heat transition is that the future renewable energy systems will be powered predominantly by renewable electricity from solar-PV, wind turbines, geothermal energy and bio-fuel, district heating systems and can provide large amounts of cost-effective flexibility to balance energy generation and demand (Olsen et al., 2008). Furthermore, an advantage of heat scenario is that it does not the rely as much on the on the capacity of the electricity grid as the all-electric scenario does (Van Leeuwen et al., 2017). Dutch policies however, are aimed more at reducing the heat loss of buildings and increasing the share of renewable energy within the power grid than to encourage district heating (Ministerie van Economische Zaken, 2016; Van Leeuwen et al., 2017).

Therefore, the study from Van Leeuwen et al. (2017) argues that Dutch national and regional policy-makers overlook options for district heating and more research should be done on district heating systems with renewable energy systems. An aspect that is not mentioned in the research from Van Leeuwen (2017) is that the policy-makers struggle with legislative issues when trying to implement collective transitions. Municipalities often do not have the legal decision-making power to implement a transition, as was mentioned by the municipality of Utrecht in the natural gas-free transitions of Utrecht Overvecht (Rijksdienst voor ondernemend Nederland, 2019). Therefore, in collective transitions community resistance has shown to be a factor that can slow down or stop the transition process. The DRIFT research institute highlights that the transition to the all-electric scenario could reduce the issue of low community acceptance, since the all-electric transition can be implemented on an individual scale (Beers et al., 2019).

To summarize there is more of a constraint to policy acceptance of the heating scenario compared to the all-electric scenario, because the heating scenario can only be implemented on a collective scale and therefore needs collective community acceptance, whereas the all-electric scenario can be implemented on an individual scale. Nevertheless, a disadvantage of the transition to the all-electric scenario is the lower potential to further increase the usage of renewable energy sources for non-building related energy usage compared to the heat scenario. Therefore, since the characteristics of each neighborhood differ the choice whether the all-electric or heat scenario is favorable should depend on the location (Slingerland personal communication, 22 May 2020). Consequently, to guide policy-maker in this decision the policy-making methodology is developed based on the literature review in the conceptual model.

The policy-making methodology for sustainable buildings

The policy-methodology for sustainable buildings consists of the following three steps.

1. Develop an overview of possible transitions scenarios
2. Analyse the three dimensions of social acceptance
3. Perform an LCA of the transitions

Developing an overview of possible transition scenarios provides a first basis for decision-making. From the social acceptance literature, interviews with experts and policy evaluation it became clear that social acceptance can constrain the adoption of the innovation. A solution that has no or too little social acceptance will not be successfully implemented. Therefore, social acceptance should be analysed first before performing the LCA study of a policy option. Finally, an LCA of the possible transitions aims to identify the most sustainable scenarios. After performing the three steps the policy-maker is recommended to select an policy option with social acceptance and high sustainability performance.

5 Discussion

Sustainable urban design has become increasingly important in order to mitigate the human impact on nature. There is a need for LCA that can be applied to sustainable urban design. This research performs LCA interpretation on buildings and relates this to sustainable urban design policies for sustainable buildings in the Netherlands.

Therefore, the research focused on **how to relate LCA results of buildings to policies for sustainable urban design and how to subsequently design policies for sustainable buildings*?***

This question is answered in three steps: 1) Review of LCA methodological advantages, disadvantages and an strategy for interpretation of LCA results 2) Interpretation of LCA results of BENG buildings in The Netherlands and relating them to policy making 3) Development of a methodology for policy-making of sustainable buildings. To increase the robustness of the results, data triangulation is used from interviews with LCA and sustainable urban design experts combined with literature review and quantitative analysis in the LCA interpretation step.

1) The main advantages of LCA methodology for sustainable urban design are that the environmental performance can be assessed while taking into account all product-life stages. Furthermore, LCA can offer incentives for sustainable transitions and comparison of environmental performance. Lastly, LCA can be a decision supporting tool for sustainable urban design.

The main weakness of LCA methodology in terms of environmental assessment is the poor assessment of local impacts and biodiversity. The environmental assessment of local impacts is poor, because In LCA methodology, all impacts from the product life cycle are added, which results in a loss of the geographical location of the impacts. However, mid-point indicators in LCA like nitrogen or sulfur emissions do have different environmental impacts depending on the local environment and can cause loss of biodiversity and acidification in some locations. The assessment of the impact of biodiversity is poor since the vast majority of LCA approaches look at biodiversity impacts by land-use and land-use change only, which are not good indicators of biodiversity impacts.

2) The LCA interpretation compares the environmental impacts of the BENG building's materials from terraced buildings with a sloping roof, terraced buildings with a flat roof, corner buildings with a sloping roof for scenarios with all-electric, gas and heat electricity generation systems. The environmental impacts are presented in annual shadow costs per m^2 of gross floor area. The contribution analysis compares how these environmental impacts are further divided into the impact of foundation, floors, roofs & facades and installations.

The LCA interpretation shows that the all-electric scenario has the lowest shadow costs and the gas scenario has the highest shadow costs and the heat scenario in between all-electric and gas. The results show the gas scenario has 21% to 43% larger environmental impact than the all-electric scenario and the heat scenario has 4 % to 16% larger impact than the all-electric scenario depending on the building type.

The contribution analysis shows that the shadow costs differences between electricity generation systems are caused by the impact of installations—as 81% to 147% of these shadow costs differences are caused by the building's number of PV panels—whereas the shadow costs of foundation, floors, roofs and facades are almost similar for different electricity generation systems.

This difference in number of PV panels between BENG buildings can be explained by the efficient heat pump technology in all-electric buildings. Due to an heat pump efficiency that can reach up to 400% in the all-electric scenario compared to a typical boiler efficiency of 70% to 80% in the gas scenario, the all-electric building needs less PV panels to comply with the BENG regulations.

BENG buildings in the gas scenario need a larger number of PV panels to achieve the almost energy-neutral design and are still less sustainable compared to BENG buildings in the all-electric and heat scenarios regarding the building's materials, because of the larger number of PV panels. Therefore, the LCA interpretation—though it is based on the newbuild BENG building—supports the policy from the Dutch government that aims for natural-gas free buildings.

The LCA interpretation suffices to draw conclusions regarding the holistic environmental performance of BENG buildings regarding the impacts of building's materials and the building related energy-usage—even though the LCA only focuses on building's materials—since the BENG buildings are designed to be almost energy-neutral and therefore sustainable during the usage phase. Nevertheless, the choice of electricity generation system influences the potential in which the non-building related energy usage can be supplied by using renewable energy sources.

For the all-electric scenario, electric demand can be supplied from PV panels or regional wind turbines. The options for the heat scenario are heat supply from waste, biomass, bio-fuel conversion, solar thermal plants, power to heat, shallow and deep geothermal energy and seasonal thermal storage. For the gas scenario, an option for sustainable gas usage to heat buildings in the Netherlands is purification of bio-gas into methane, however a disadvantage is that this is a costly technology. Therefore, the heat scenario and thereafter the all-electric scenario have the most potential to increase the usage of renewable energy sources. Increasing the usage of renewable energy sources is another policy goal by the Dutch government and a way to increase the sustainability of buildings.

Besides the comparison of the environmental performance of electricity generation systems, the LCA interpretation seems to suggest that buildings with a sloping roof design and with a larger number of adjacent buildings are more sustainable compared to buildings with a flat roof design and less adjacent buildings. Nevertheless, these results are only suggested and not proven by LCA interpretation since possibly other differences between the buildings, like the gross floor area, could also impact the environmental performance of the buildings.

3) To design policies for BENG buildings the LCA interpretation provides the following suggestions. Policy-makers are advised not to go for the gas scenario since it is less sustainable compared to the all-electric and heat scenarios regarding the building's materials and building related energy usages, even though the gas buildings has a larger number of PV panels. Besides these disadvantages the possibilities in the gas scenario for using renewable energy supply for non-building related energy usage are also limited and costly compared to the all-electric and heat scenarios. Furthermore it is advised to prioritize a larger number of adjacent buildings and use the sloping roof design, as the LCA interpretation seems to suggest this improves the environmental performance of buildings.

The LCA interpretation does not reflect the local environmental impacts nearby the buildings as well as the impacts on local biodiversity. However, the LCA interpretation provide a holistic perspective of the environmental performance since it encompasses the environmental impacts of all life cycle stages of building's materials from waste to disposal. The LCA interpretation is in line with policies from the Dutch government as well as the interviewed LCA and sustainable urban design experts, who suggests the transition towards natural gas-free buildings.

Furthermore, as the LCA interpretation as well as the Dutch governmental policy suggest that natural-gas free buildings increase the sustainability performance, the social acceptance of the ongoing natural-gas free transition is evaluated for existing buildings. As the LCA interpretation focuses on BENG buildings it can only suggest that also within existing buildings the transition to natural-gas free living may increase the sustainable performance of buildings.

Two policy options for sustainable design of buildings in existing buildings—which are in line with the LCA interpretation that the gas scenario is the least sustainable—are already implemented by the Dutch government and supported by sustainable urban design expert Slingerland. These policy options are the transition to the heat scenario by a collective implementation of central city heating systems or the transition to the all-electric scenario by implementation of heat pumps in buildings on an individual scale.

A low level of community acceptance is a constraining factor in the transition to the heat scenario. There is more of a constraint to policy acceptance of the heating scenario compared to the all-electric scenario, because the heating scenario can only be implemented on a collective scale and therefore needs collective community acceptance, whereas the all-electric scenario can be implemented on an individual scale. Experts and the municipalities of Utrecht and Amsterdam show concerns regarding ensuring procedural and distributional justice for citizens and had difficulties guiding the transitions process. Therefore the transition to the all-electric scenario which can take place on an individual scale could avoid the issue of low community acceptance.

To guide policy-makers in which policy to choose a three step policy-methodology for sustainable buildings is developed. The first step is to make an overview of possible transitions. The second step is to analyse the disadvantages and advantages regarding the three dimensions of social acceptance. The third step is to perform LCA analysis for each option. After going through all the three steps, the policy-maker can decide which policy to choose by weighting the advantages and disadvantages of each option.

A limitation of this research is that the goal and scope, inventory and impact assessment steps of the LCA have been executed by W/E adviseurs (2019). Therefore, the transparency is decreased particularly since no substantiation could be given on the inventory selection and no comparison could be performed between different weighting methods in the impact assessment step. However, the choice to use the LCA data from the study from W/E adviseurs is justifiable since certified LCA expert Jeannete Levels from LBP|SIGHT was part of the research team and the research data are included in the Dutch National Environmental Database. Therefore the LCA study from W/E adviseurs (2019) can be considered reliable.

Furthermore a limitation in the LCA study W/E adviseurs (2019), which is also a limitation in this research is that using shadow costs in LCA assessment is controversial. Nevertheless this step was essential in the LCA interpretation of this research to support decision-making and relate the results to policy-making. Since the weighting step was performed by W/E adviseurs and no access was available to LCA results in environmental impact categories, no comparison of different weighting methods could be performed. Therefore, to increase the robustness of the LCA interpretation data triangulation is used and the LCA interpretation is supported by the interviewed LCA and sustainable urban design experts as well as the Dutch governmental policies.

Additionally, a limitation is that the policy-making methodology does not fully operationalize how to measure social acceptance of a policy. Therefore it leaves the policy-makers with subjective decisions regarding their perception of the social acceptance of a policies. This research provides policy-makers with the theoretical framework on social acceptance and it does identify that in the transition to the heat scenario low community acceptance could be a constraining factor. The social acceptance literature describes the community, socio-political and market acceptance dimensions of social acceptance, however only the community acceptance dimension was highlighted by sustainable urban design experts in this research. Therefore an suggestion for further research is to analyze the social acceptance on the community, socio-political and market acceptance dimensions of BENG buildings. Regarding the policy recommendation in this research it is relevant to research whether there is a social acceptance not to go for the gas scenario for BENG buildings in newbuild projects.

Furthermore, the LCA interpretation in this research suggest buildings with a sloping roof design and more adjacent buildings are most sustainable. Nevertheless, this was not proven due to the problem of causality and no support for these findings was found in other research. Therefore further research on the sustainability impacts of roof design and the number of adjacent building’s is suggested.

Additionally, the conceptual model in this research provides an innovative contribution to the literature. Nevertheless, this conceptual model has not been tested in this research since the market acceptance and socio-political dimensions of social acceptance have not been reviewed. An suggestion for further research is to apply the policy-making methodology and combine a study on the social acceptance of the three dimensions with an LCA. This further research could identify the advantages and disadvantages of the conceptual framework.

The methodology for the contribution analysis in this research provided deeper insight on the LCA study from W/E adviseurs (2019). A weakness from this methodology to perform LCA interpretation from another study is the increased risk of misinterpretation, since the goal and scope, inventory and impact assessment steps have been performed by other researchers. To avoid misinterpretation in this research apart from an extensive gray literature review of BENG buildings regulations from the Dutch government and study of the LCA results from W/E adviseurs (2019), an interview was held with Erik de Jong who was part of the previous research team. Furthermore a disadvantage of the LCA interpretation methodology is that the methodological choices by the previous research teams cannot be justified or evaluated. Nevertheless, the methodological advantage of LCA interpretation is that environmental performance results can be applied for policy-making as an objective decision-making support tool for sustainable urban design. The applied data-triangulation in this research by conducting interviews with LCA and sustainable urban design experts, literature review, policy evaluation and LCA interpretation increases the robustness of the results.

6 Conclusion

This research answered the question: **how to relate LCA results of buildings to policies for sustainable urban design and subsequently how to design policies for sustainable buildings*?***

This question is answered in the following three steps: 1) Review of LCA methodological advantages, disadvantages and an strategy for interpretation of LCA results 2) Interpretation of LCA results of BENG buildings in The Netherlands and relating them to policy making 3) Development of a methodology for policy design of sustainable buildings.

LCA methodology can assess the environmental performance while taking into account all product-life stages. Furthermore, LCA can offer incentives for sustainable transitions and comparison of environmental performance, which makes LCA a decision supporting tool for sustainable urban design. Nevertheless disadvantages of using LCA for sustainable urban design are the poor assessment of local impacts and biodiversity.

The LCA interpretation shows that the all-electric scenario has the lowest shadow costs and the gas scenario has the highest shadow costs, and the heat scenario in between all-electric and gas. The results show the gas scenario has 21% to 43% larger environmental impact than the all-electric scenario and the heat scenario has 4 % to 16% larger impact than the all-electric scenario depending on the building type.

The contribution analysis shows that the shadow costs of BENG buildings materials differ between the all-electric, heat and gas scenarios, which is caused for 81% to 147% by differences in the number of PV panels. BENG building with the gas scenario need a larger number of PV panels to achieve the almost energy-neutral design and are still less sustainable compared to the all-electric and heat scenarios regarding the building’s materials, because of the larger number of PV panels. Furthermore the research suggest that having a sloping roof design and more adjacent buildings increases the sustainability.

The LCA interpretation is related to the policy recommendations. For BENG buildings the recommendation is not to go for the gas scenario, since this is the least sustainable. Consequently the LCA interpretation supports the Dutch governmental policy for the natural-gas free transition since the LCA interpretation showed the gas scenario is less sustainable and furthermore the gas scenario has lower potential to further increase the usage of renewable energy for non-building related energy usage. Therefore, the LCA interpretation suggests that policies with an transition to the all-electric scenario or with an transition to the heat scenario improve the environmental performance of buildings.

Sustainable urban design policy expert Mangnus and the municipalities of Utrecht and Amsterdam showed regarding the policy with a transition to the heat scenario that low community acceptance can be a constraining factor. There is more of a constraint to policy acceptance of the heating scenario compared to the all-electric scenario, because the heating scenario can only be implemented on a collective scale and therefore needs collective community acceptance, whereas the all-electric scenario can be implemented on an individual scale.

To guide policy-makers to choose the heat or all-electric transition a three step policy-methodology for sustainable buildings is developed. The first step is to make an overview of possible transitions. Secondly, the disadvantages and advantages of each option can be analysed regarding the socio-political, community and market acceptance. Thirdly, LCA can be performed for each option. After going through all three steps, the policy-maker can decide which options to choose by weighting the advantages and disadvantages of each option. The three step policy-making methodology could be used to design policies for sustainable buildings, though more research on the limitations and advantages of this methodology is needed.

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8 Appendix

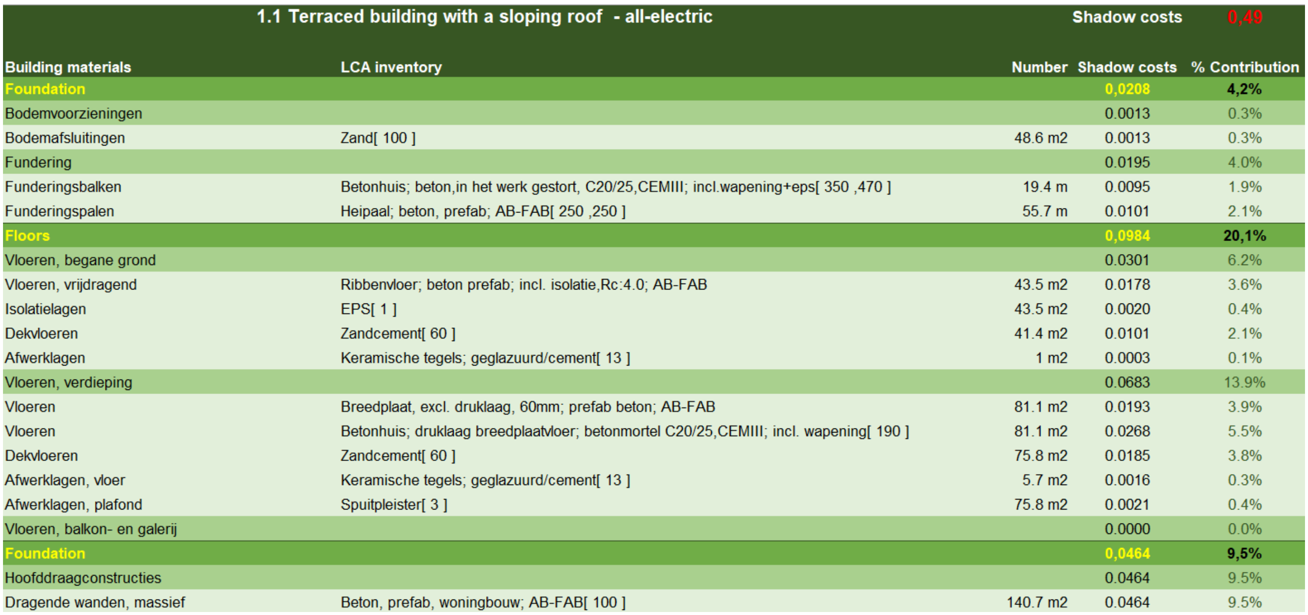
The appendix provides the details of the performed calculations in excel during this research. Firstly, an overview is given of the structure in the excel document. Secondly, the calculations for all the charts are explained.

Overview of excel

The attached excel document includes all the calculations of the LCA interpretation step. The numbers in the first tab called 'Ratsma Thesis Calculations' which are highlighted in colors come from the LCA study on BENG buildings from W/E adviseurs (2019). All the numbers which are not highlighted in colors and all charts are made during the thesis research.

The LCA inventory and impact assessment steps from W/E adviseurs (2019) are given in the subtabs. The inventory data are listed in the Dutch language since the LCA study from W/E adiviseurs is performed by a Dutch research team including an certificied LCA expert. The excel subtabs 1.1 to 3.3 contain the LCA inventory and impact assessment results regarding the terraced buildings with a sloping roof, terraced buildings with a flat roof, corner building with the all-electric, heat and gas scenarios. Screenshot 1 provides an overview of the first part of the excel subtab 1.1 Terraced building with a sloping roof and the all-electric scenario.

Sceenshot 1 'Tab 1.1 Terraced building with a sloping roof – all-electric'



	1.1 Terraced building with a sloping roof - all-electric		Shadow costs	0,49
Building materials	**LCA inventory**	**Number**	**Shadow costs**	**% Contribution**
Foundation			**0,0208**	**4,2%**
Bodemvoorzieningen			0.0013	0.3%
Bodemafsluitingen	Zand[100]	48.6 m2	0.0013	0.3%
Fundering			0.0195	4.0%
Funderingsbalken	Betonhuis; beton,in het werk gestort, C20/25,CEMIII; incl.wapening+eps[350 ,470]	19.4 m	0.0095	1.9%
Funderingspalen	Heipaal; beton, prefab; AB-FAB[250 ,250]	55.7 m	0.0101	2.1%
Floors			**0,0984**	**20,1%**
Vloeren, begane grond			0.0301	6.2%
Vloeren, vrijdragend	Ribbenvloer; beton prefab; incl. isolatie,Rc:4.0; AB-FAB	43.5 m2	0.0178	3.6%
Isolatielagen	EPS[1]	43.5 m2	0.0020	0.4%
Dekvloeren	Zandcement[60]	41.4 m2	0.0101	2.1%
Afwerklagen	Keramische tegels; geglazuurd/cement[13]	1 m2	0.0003	0.1%
Vloeren, verdieping			0.0683	13.9%
Vloeren	Breedplaat, excl. druklaag, 60mm; prefab beton; AB-FAB	81.1 m2	0.0193	3.9%
Vloeren	Betonhuis; druklaag breedplaatvloer; betonmortel C20/25,CEMIII; incl. wapening[190]	81.1 m2	0.0268	5.5%
Dekvloeren	Zandcement[60]	75.8 m2	0.0185	3.8%
Afwerklagen, vloer	Keramische tegels; geglazuurd/cement[13]	5.7 m2	0.0016	0.3%
Afwerklagen, plafond	Spuitpleister[3]	75.8 m2	0.0021	0.4%
Vloeren, balkon- en galerij			0.0000	0.0%
Foundation			**0,0464**	**9,5%**
Hoofddraagconstructies			0.0464	9.5%
Dragende wanden, massief	Beton, prefab, woningbouw; AB-FAB[100]	140.7 m2	0.0464	9.5%

The LCA inventory data have directly been weighted and the shadow costs of the building's materials has been calculated. As described in the methodology section, The Dutch National Environmental Database (NMD version 3.0) is used for the impact assessment in combination with the "SKB bepalingsmethode" version 3.0 from the Dutch Quality Building Foundation which is used for the weighting step. The first excel tab called 'Ratsma Thesis Calculations' is used for the contribution analysis in the research, and substantiates on the LCA inventory and impact assessment results from subtabs 1.1 to 3.3.

Calculations for the overview of results chart 1 and 2

Chart 1 ‘Annual shadow costs of building’s materials from BENG buildings’

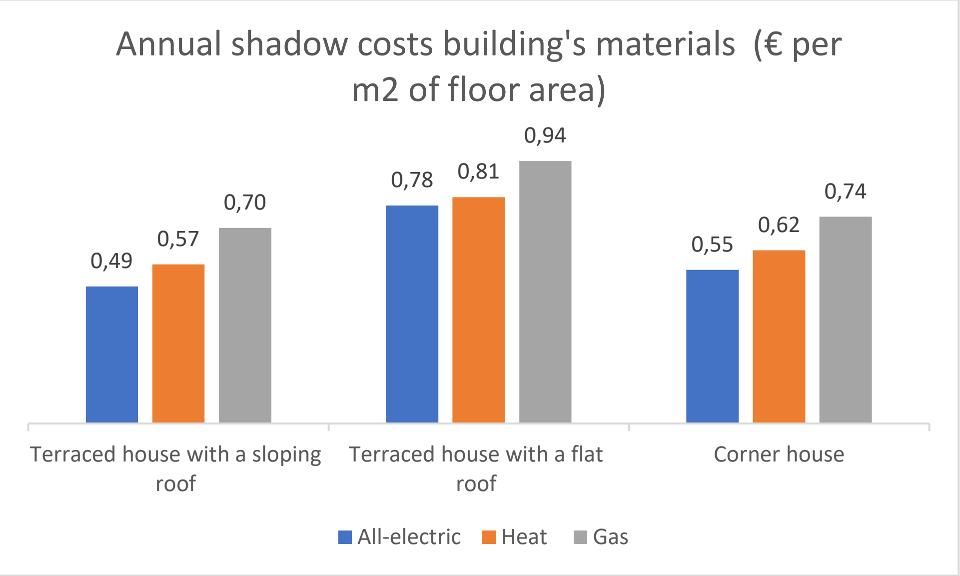


Chart 1 provides an overview of the shadow costs found in the LCA study from W/E adviseurs (2019). So in screenshot 1 the number 0.49 highlighted in red represents the annual shadow costs for a terraced house with a sloping roof and the all-electric scenario.

Chart 2 ‘Percentual impact of buildings materials’

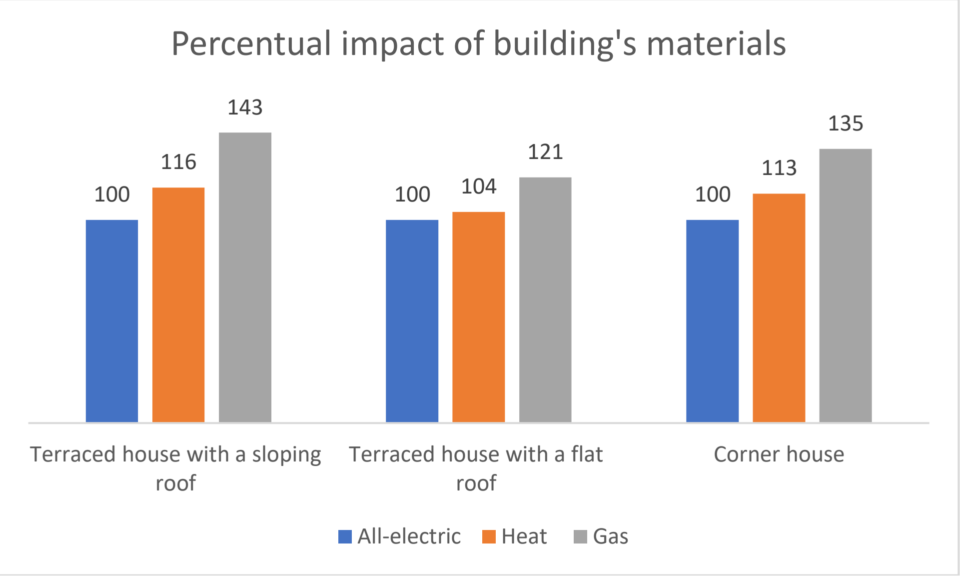


Chart 2 takes a closer look on the magnitude of these percentual differences of the shadow costs between the all-electric, heat and gas scenarios. It takes the all-electric scenario as reference and assumes 100% impact.

The percentual impact is calculated based on the data in chart 1 with the following formula.

$$\text{percentual impact} = \frac{\text{shadow costs of heat or gas building}}{\text{shadow costs of all} - \text{electric building}} \times 100\%$$

This means for example that in the heat scenario and the terraced house with a sloping roof the percentual impact is:

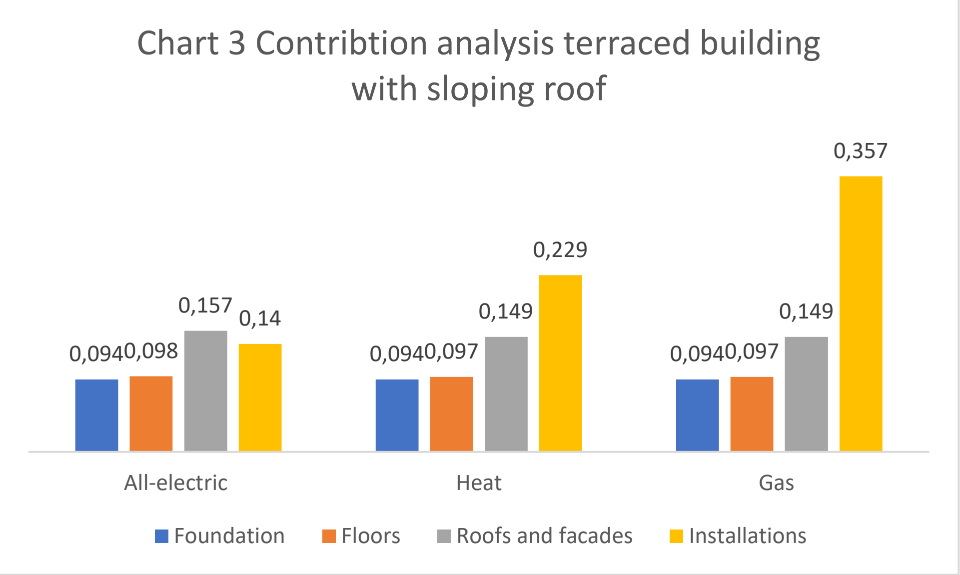
$$\frac{0.59}{0.49} \times 100 = 116\%$$

Therefore it can be concluded that for a terraced house with a sloping roof the shadow costs are 16% larger for the heat scenario compared to the all-electric scenario.

Calculations for the contribution analysis charts 3 to 8

Screenshot 1 shows the four categories in the contribution analysis namely foundation, floors, roofs and facades, installations are marked in yellow. All buildings materials in the LCA inventory are divided in one of these four categories.

Chart 3 compares all-electric, heat and gas scenarios according to contribution of foundation, floors, roofs and facades, and installations for the terraced building with a sloping roof. In the main excel tab 'Ratsma Thesis Calculations' the contribution has been calculated by adding the shadow costs of all building's materials in each of the four categories.



Charts 4 and 5 are made in a similar way for the two other building types. Chart 6 presents the number of PV panels as given by W/E adviseurs (2019). Chart 7 is made in a similar way as charts 3,4 and 5.

Chart 8 is calculated based on the results of chart 1 and chart 7. Table 1 shows the data from Chart 1, and table 2 shows the data of Chart 7.

Table 1 ‘Data from chart 1’

Total shadow costs	**All-electric**	**Heat**	**Gas**
Terraced house with a sloping roof	0,49	0,57	0,70
Terraced house with a flat roof	0,78	0,81	0,94
Corner house	0,55	0,62	0,74

Table 2 ‘Data from chart 7’

Shadow costs PV panels	**All-electric**	**Heat**	**Gas**
Terraced house with a sloping roof	0,068	0,165	0,264
Terraced house with a flat roof	0,163	0,207	0,294
Corner house	0,062	0,151	0,232

Table 1 presents the total shadow costs of buildings with the all-electric, heat and gas scenarios. Firstly the additional shadow costs for heat and gas scenarios compared to the all-electric scenario are calculated.

Table 3 ‘Additional shadow costs compared to all-electric’

Additional shadow costs compared to all-electric	**Heat**	**Gas**
Terraced house with a sloping roof	0,08	0,21
Terraced house with a flat roof	0,03	0,16
Corner house	0,07	0,19

So the value 0.08 in table 3 for heat means the additional shadow costs of the heat scenario compared to the all-electric scenario is $0.57 - 0.49 = 0.08$ for the terraced building with a sloping roof.

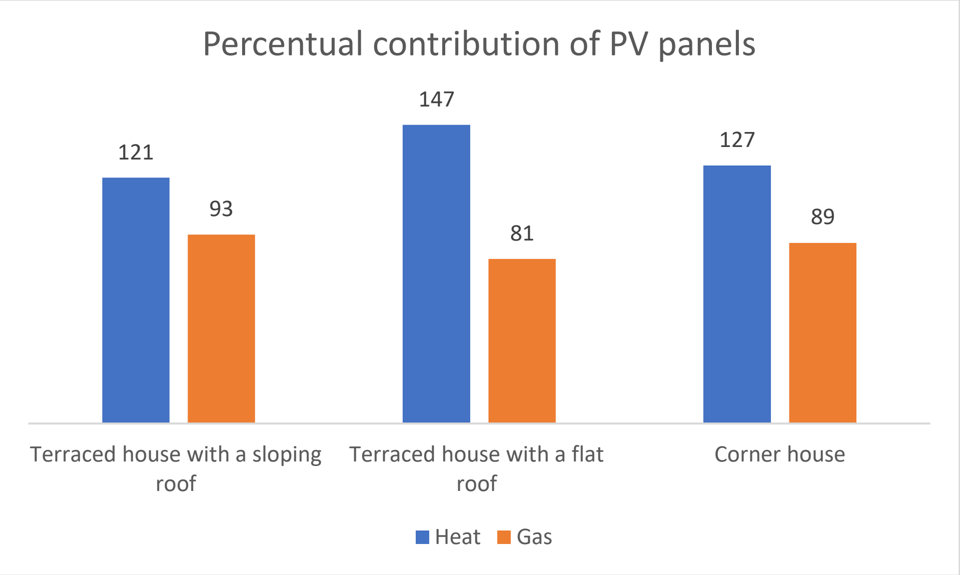
Secondly the additional shadow costs by PV panels for heat and gas scenarios compared to the all-electric scenario are calculated in the same way.

Table 4 ‘Additional shadow costs compared to all-electric by PV panels’

Additional shadow costs compared to all-electric by PV	**Heat**	**Gas**
Terraced house with a sloping roof	0,097	0,196
Terraced house with a flat roof	0,044	0,129
Corner house	0,089	0,17

Consequently the percentual contribution of PV panels to the shadow costs differences of all-electric, heat and gas scenarios is calculated in chart 8. Chart 8 is a comparative contribution analysis where the heat and gas scenarios are compared to the best-performing all-electric scenario. The percentual contribution of PV panels to the shadow costs differences between all-electric, heat and gas scenarios are calculated.

Chart 8 ‘ Percentual contribution of PV panels’



The data in chart 8 are calculated with the formula:

$$Percentual\ contribution\ of\ PV\ panels = \frac{additional\ shadow\ costs\ by\ PV}{additional\ shadow\ costs} \times 100\%$$

So the value 121% means the terraced building with a sloping roof in the heat scenario has a shadow costs difference by PV panels compared to the all-electric scenario which equals 1.21 times the total shadow costs difference compared to the all-electric scenario.

$$\frac{0.097}{0.08} \times 100 = 121\%$$