



## Environmental assessment of Smart City Solutions using a coupled urban metabolism—life cycle impact assessment approach

**Ipsen, Kikki Lambrecht; Zimmermann, Regitze Kjær; Nielsen, Per Sieverts; Birkved, Morten**

*Published in:*  
International Journal of Life Cycle Assessment

*Link to article, DOI:*  
[10.1007/s11367-018-1453-9](https://doi.org/10.1007/s11367-018-1453-9)

*Publication date:*  
2019

*Document Version*  
Peer reviewed version

[Link back to DTU Orbit](#)

*Citation (APA):*  
Ipsen, K. L., Zimmermann, R. K., Nielsen, P. S., & Birkved, M. (2019). Environmental assessment of Smart City Solutions using a coupled urban metabolism—life cycle impact assessment approach. *International Journal of Life Cycle Assessment*, 24(7), 1239-1253. <https://doi.org/10.1007/s11367-018-1453-9>

---

### General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

# 1 Environmental assessment of Smart City 2 Solutions using a coupled Urban Metabolism 3 - Life Cycle Impact Assessment approach 4

5 Kikki Lambrecht Ipsen <sup>a</sup>, Regitze Kjær Zimmermann <sup>a,d</sup>, Per Sievert Nielsen <sup>b</sup>, Morten Birkved <sup>c</sup>

6 <sup>a</sup> *Technical University of Denmark, Division for Building Design, DTU Civil Engineering, Brovej, Building 118,*  
7 *Kongens Lyngby, 2800, Denmark*

8 <sup>b</sup> *Technical University of Denmark, Division for System Analysis, DTU Management Engineering, Produktionstorvet*  
9 *Building 424, Building 426, Kongens Lyngby, 2800, Denmark*

10 <sup>c</sup> *Technical University of Denmark, Division for Quantitative Sustainability Assessment, DTU Management*  
11 *Engineering, Produktionstorvet Building 424, Kongens Lyngby, 2800, Denmark*

12 <sup>d</sup> *Danish Building Research Institute, Aalborg University Copenhagen, A C Meyers Vaenge 15, DK-2450 Copenhagen*  
13 *SV, Denmark*

## 14 Abstract

15 *Purpose.* The purpose of the study is to quantify the environmental performance of Smart City Solutions at urban  
16 system level and thus evaluate their contribution to develop environmentally sustainable urban systems. Further, the  
17 study illustrates how this quantification is conducted.

18 *Methods.* The case city chosen in our modelling is Copenhagen, where seven Smart City Solutions are introduced:  
19 Green Roofs, Smart Windows, Pneumatic Waste Collection, Sensorized Waste Collection, Smart Water meters,  
20 Greywater Recycling and Smart Energy Grid. The assessment is conducted using a fused Urban Metabolism (UM) -  
21 Life Cycle assessment (LCA) approach, referred to as UM-LCA. The UM-LCA uses metabolic flows across an urban  
22 system as inputs and outputs in an LCA. All life cycle stages of the metabolic flows can be accounted for by using this  
23 approach and burden shifting from one stage to another is made quantifiable and hence transparent. The impact  
24 assessment is conducted using the ReCiPe method.

25 *Results and discussion.* The results obtained for the midpoint indicator, Global Warming Potential (GWP), shows  
26 reduced environmental performance effect at 75% relative to a business as usual reference scenario by introducing  
27 Smart Windows. Furthermore, the GWP indicator shows an environmental improvement of 10% for a Smart Energy

28 Grid solution. Introduction of Pneumatic Waste Collection or Greywater Recycling reveals a minor negative  
29 performance effect of 0,76% and 0,70% respectively for GWP. The performance changes of in terms of GWP for the  
30 remaining solutions are so small, that these are expected to be within the uncertainty of the calculations. To obtain  
31 endpoint indicators (damages) the entire palette of ReCiPe indicators are included. The results of the endpoint indicator  
32 assessment yield a tendency similar to the one observed for climate change.

33 *Conclusions.* It is found that the implementation of Smart City Solutions generally have a negative influence on the  
34 environmental sustainability performance of an urban system. The limited positive influence from the Smart City  
35 Solutions is due to burden shifting from the direct impacts of the urban system to embedded impacts which are out of  
36 sight for most policy makers. The influence of the Solutions on Copenhagen is generally small, due to a focus on  
37 reducing in areas, that are not a large environmental burden in Copenhagen. The results are not sufficient to discard the  
38 idea of using Smart City Solutions to reduce environmental impacts, but highlight the importance of choosing solutions  
39 with the right focus and optimizing the design to best fit the intensions.

## 40 Keywords

41 Smart City, UM-LCA, Life Cycle Assessment, Urban Metabolism, Burden Shifting, Urban design, Urban systems

## 42 1. Introduction

43 Cities are expanding and increasing in numbers. Around the world people are migrating towards cities, creating more  
44 and larger urban areas. In the developed world 75% of the population live in urbanized areas and the number is still  
45 increasing (Larsen et al 2011). This number is lower in the developing countries, however, migration is happening at a  
46 higher rate here (Larsen et al 2011). It is estimated that every week more than one million people either migrate to or  
47 are born into cities in the developing world (Townsend 2013). More than half the world's population live in cities today  
48 and it is expected that this number will further increase in the coming decades.

49 At the same time technology is developing at a rapid pace and access to technology is also rapidly increasing. This is  
50 the basis for novel urban system developments such as the Smart City (SC). SC is a widely-used concept for cities,  
51 especially in Europe. The concept generally describes solutions which use technology of some form to improve the  
52 performance of the urban system.

53 These Smart City Solutions (SCSs) have different ways of improving the urban system. The smart technology is  
54 claimed to be able to improve social, governmental, economical, or environmental aspects of the urban system (Cocchia  
55 2014; Nam et al 2011; Neirotti et al 2014; Townsend 2013). A general trend is that the SCSs can make the urban system

56 more efficient. Such efficiency improvements include reducing energy use or reducing transport by using intelligent  
57 systems and data to optimize the efficiency of the system. Rethinking or optimizing an existing system by introducing a  
58 new technology so that the technology become more efficient is the approach that often frames the “smart” concept.  
59 These SCSs can reduce resource consumption of the urban system such as electricity, water and transport, as the  
60 increased effectiveness are intended to reduce energy consumption, whereby the direct emissions to the environment are  
61 lowered. However, implementing the SCSs also means that new products are introduced which may increase indirect  
62 emissions to the environment (e.g. emissions occurring in relation to the production of the smart technology and hence  
63 often far away from the urban system receiving the smart technology).

64 There is little research on the subject of the environmental burden induced by dedicated “smart” urban system  
65 technologies in the existing literature. The method used to conduct the assessment (see paragraphs 2.2) of the  
66 technologies, presented in our paper, has been developed and tested by Goldstein et al. (2013) on five different cities.  
67 Goldstein et al. (2013) found that the assessment method applied provides improved quantification of mass and energy  
68 flows through cities and that the method enables identification of the dominant sources of cities’ environmental  
69 footprint. In terms of environmental assessments of Smart Cities or technologies qualifying as SCSs, assessments have  
70 been conducted previously, however the assessments have not been related to the urban system and thus not how the  
71 SCS may alter the environmental performance of urban systems (Malik et al. 2013; Zadeh et al. 2013; Yang et al. 2008;  
72 Villareal et al. 2004; Punkkinen et al. 2012; Memon 2007; Bianchini 2011). However, these previous assessments have  
73 proven valuable for our study, as they provide quantification of the (energy, water, and transport) saving potentials  
74 when a SCS is operating as a part of a city system. Qualitative analysis of case cities have previously been carried out  
75 accompanied by research on specific technologies. An example of such a qualitative analysis is the uncompleted eco-  
76 city, Caofeidian (China) presented by Joss et al. (2013), where the use of SCSs in the city is discussed. Furthermore, an  
77 analysis of Barcelona’s initiatives to become a Smart City has been analysed at a strategic level (Bakıcı et al. 2012).

78 The literature study hence reveals that no previous studies exists on how the implementation/application of smart  
79 technologies affects the environmental performance of the urban systems in which these technologies are implemented.  
80 The goal of this assessment is to gain insight into whether the SCSs can contribute to the development of environmental  
81 sustainable cities. In our paper, implementation of SCSs in existing urban systems is assessed to quantify the induced  
82 and/or avoided environmental impacts a technology may trigger when implemented in a specific urban system. Such  
83 impact/impact reduction trade-offs may arise from e.g. reducing energy consumption in the building operation stage by  
84 implementing SCSs to regulate energy consumption. In this study the environmental performance of seven SCSs

85 implemented in the urban system of Copenhagen are tested. The solutions tested are all designed to either save energy  
86 (i.e. electricity) consumption in buildings during operation, reduce transport demands and/or reduce water consumption.  
87 Building energy and transport was chosen due to the significance of these urban metabolic flows (see Goldstein et al.  
88 (2013)) in relation to the environmental performance of cities, while “water” was chosen due its frequent occurrence in  
89 the environmental debate today. The SCSs connected to changing personal behavior, such as personal transport  
90 patterns, have not been included in our assessment since the method applied is not capable of taking personal transport  
91 into consideration. The ‘smart’-aspects in the solutions tested are limited to use of Information and Communication  
92 Technology (ICT) and the chosen solutions have to state a potential for environmental savings when used. The solutions  
93 are evaluated using Life Cycle Assessment (LCA) coupled with Urban Metabolism (UM), to assess if the smart  
94 technologies lower the environmental burden of the urban system, or if their contribution is only to shift the burden  
95 within the smart technology solutions value chain (e.g. by moving impacts outside the urban system). In other words,  
96 whether the SCSs are exacerbating the environmental performance of the urban system.

## 97 2. Methods

### 98 2.1. Case study

99 The purpose of this study is to quantify environmental impacts of SCSs when implemented in an urban system.

100 Therefor a case urban system has been selected and examples of SCSs selected. Copenhagen is chosen as the case urban  
101 system, and seven SCSs are selected and assessed. The SCSs selected are all associated with buildings in the urban  
102 system, including the supply of materials and resources to buildings and waste systems connected to them. A “business  
103 as usual” scenario is our reference and includes an assessment of the urban system without implementation of SCSs. In  
104 additional scenarios, the seven SCS are individually implemented on the system. The aim of this approach is to  
105 illustrate the effect of the individual solutions in reference-scale to the existing urban system.

106

#### 107 **Urban system case**

108 Copenhagen is chosen as the urban system case because of its proximity to the Technical University of Denmark,  
109 availability of data and Copenhagen’s ambitious environmental goals for the future years such as e.g. becoming CO<sub>2</sub>  
110 neutral by 2025 (City Hall 2009). The boundaries of the system are defined by the geographical boundaries of the city  
111 of Copenhagen, including the municipal of Copenhagen and the municipal of Frederiksberg, see Figure 1. In the  
112 following the geographical area occupied by the urban system will simply be referred to as Copenhagen. The reference  
113 year in our analysis is 2013, as this is the most recent year with actual (non-projected) data available at the initiation of

114 the work. In the beginning of the third quarter of 2013 the population of Copenhagen was 664.338 (Danmarks statistik  
115 2013) and it occupied an area of 85,2 km<sup>2</sup> (Danmarks statistik 2016). It results in a population density of 7800  
116 citizens/km<sup>2</sup>.

117

### 118 **Smart City Solutions**

119 A considerable number of SCSs exists. The chosen solutions are therefore limited to solutions intended for buildings  
120 that rely on and/or make use of ICT. This means that the relevant SCSs are limited to acting on the building or the  
121 supply of materials and resources and the connected waste systems. Relying on and/or making use of ICT means that  
122 the smart/technology aspect is fulfilled. Furthermore, a relevant SCS must claim to improve the environmental  
123 performance (i.e. the solutions could yield increased saving potential when implemented in the city), as this is a basis  
124 for the investigation.

125 Furthermore, a relevant SCS must be implementable in an urban system, but not necessarily be a dedicated urban  
126 solution that functions in urban environments exclusively. Finally, the solution must be beyond the ideation phase and  
127 well documented/described, to assure a sufficient data quality/availability, and the selected solutions must be relevant to  
128 Copenhagen in terms of climatic conditions.

129 Seven solutions have been identified to fulfill all the listed criteria and they are summarized in table 1. The solutions are  
130 split into four domains: Building, waste, water, and power. Even though the solutions are within the same subject and  
131 all fulfill the same criteria, they are still very different. Some solutions (such as Sensorized Waste Collection (SWC),  
132 Smart Water Meter (SWM) and Smart Energy Grid (SEG)) work by adding an ICT element to existing mechanical  
133 systems, while others require additional installation of a new mechanical system where the ICT is pre-installed (e.g.  
134 Pneumatic Waste Collection (PWC)). The solutions also work at different urban levels. Some are operating at a  
135 building level (e.g. Green roofs (GRo), Smart windows (SWi) and Greywater Recycling (GRe)), while other are  
136 operating at urban system or city level, e.g. the waste technology. The seven SCSs are implemented individually on the  
137 case city, Copenhagen, resulting in seven scenarios.

138

### 139 [2.2. Urban Metabolism Coupled with Life Cycle Assessment](#)

140 UM is a 'big picture' environmental performance quantification of urban regions (Kennedy et al 2011). UM accounts  
141 for the consumption related flows of the city: The inputs, outputs and storage of energy, water, nutrients, materials and  
142 wastes, as shown in Figure 2. It is possible to calculate the urban metabolism using several methods (Pincetl et al 2012),

143 however, the methods are too complex to both calculate and communicate, or too simple to provide reliable results  
144 (Goldstein 2013). A combination of UM and Life Cycle Assessment (LCA) have shown to be a relevant method  
145 (Goldstein 2013). LCA accounts for exchanges between the technosphere and ecosphere through all the life cycle stages  
146 of a service like the services provided by the metabolic flows of an urban system. By using the LCA methodology in  
147 combination with the UM all life cycle stages in a metabolic flow are accounted for, and burden shifting from one stage  
148 to another is made transparent. Furthermore, the LCA framework is far more developed than UM, for instance in terms  
149 of standardisation; e.g. ISO standards exist for LCA (ISO 2006a; ISO 2006b), as well as a user guidelines (European  
150 Commission 2010). This makes the assessment form reproducible, more credible and transparent compared to UM.  
151 Moreover, databases have been developed containing datasets that accounts for elementary flows of unit processes,  
152 easing the use of LCA framework compared to UM.  
153 Fused UM-LCA uses the metabolic entity (i.e. the urban system) as offset for the LCA. This is illustrated in Figure 3.  
154 The LCA methodology is intended to account for process induced elementary flows in all life cycle stages, contrary to  
155 the UM. Hence for the LCA it is not important to distinguish between processes in a metabolic flow which occur inside  
156 or outside the urban system. When a SCS is introduced, the altered urban system and altered metabolic flows are  
157 assessed following the LCA framework considering elementary flows in all life cycle stages. This is illustrated in  
158 Figure 4. In the operation stage, the SCS is most often expected to provide a consumption saving, due to avoided  
159 metabolism. The metabolisms (or LCIs in LCA terms) for Copenhagen and for the SCSs can be seen in Supporting  
160 Information to this paper.

161

### 162 2.3. System boundaries

163 When relying on UM-LCA the assessment includes all lifecycle stages of the considered metabolic flows from cradle to  
164 grave. The system boundaries are illustrated in Figure 5, where the excluded aspects are marked with red. The direct  
165 impacts from the urban system and hence from the SCSs include consumption of electronics, food, tourism, buildings,  
166 power, consumer goods, water and finally transport and freight taking place inside Copenhagen. The embedded impacts  
167 include ground water extraction, raw material extraction, agriculture, power production, production in general and  
168 transport between phases and sub suppliers. Due to lack of data on construction phase of buildings, installation and of  
169 the actual SCSs, and data storage for all the data delivered/used by the SCSs are excluded. The exclusion of SCS  
170 installation and data storage is expected to lead to underestimation of the impact potential for the SCSs. The exclusion  
171 of building construction phase in the calculations is expected to lead to an underestimation of the impact potential for

172 all scenarios. Furthermore, the embedded impacts resulting from tourism in Copenhagen involving transport of tourists  
173 to and from Copenhagen, mainly via ship or aircraft, have been excluded also due to lack of data. Exclusion of  
174 embedded impacts from tourism might also lead to an underestimation of the impact potential for all scenarios.

175

## 176 2.4. System modeling

177 The modelling is aimed at assessing the change in the system which occurs when an SCS is introduced to the urban  
178 system, in alignment with the intended purpose of our assessment. In this way, it is possible to quantify how the  
179 individual SCS affects the urban system's environmental performance. The modeling and quantification of the urban  
180 system inventory is done in GaBi, version 7.2.1. The database used is Ecoinvent 3.1. In our case, a process-based LCA  
181 with a consequential modeling LCA approach is used. A consequential modeling approach is obvious to use, as the  
182 SCSs have an indirect impact on the environmental performance of the urban system by reducing various metabolic  
183 flows. The consequences of these impact changes on the city are assessed and quantified. However, GaBi does not  
184 allow for a consistent consequential modeling approach with the Ecoinvent database, and therefore attributional  
185 modeling using allocation at the point of substitution (APOS) is applied in the Ecoinvent database (background system).  
186 In accordance with the consequential modeling approach multifunctional processes are modelled using system  
187 expansion in the foreground system. This means that the system boundaries are expanded to include the life cycle  
188 inventory of the by-product(s). This is done for the waste scenario cases when incineration of a product yielded heat  
189 and/or electricity. In these cases, system expansion includes the production of heat and electricity as avoided  
190 productions, thereby reducing the impact potentials of the waste process. System expansion is also conducted when  
191 products are recycled. The processes used to model the metabolic flows in the city and the SCSs can be seen in the  
192 Supporting Information to this paper.

## 193 **Implementation of Smart City Solutions in the City**

194 Each solution is assessed in a Copenhagen context, and evaluated in accordance with how implementation of a given  
195 SCS may affect the environmental performance of the urban system. Each solution is implemented at 100% and each  
196 solution one at a time, meaning that e.g. in the GRo scenario, Green Roofs is the only solution implemented and it is  
197 implemented 100%. 100% implementation does, however, not mean that e.g. *all* roofs are converted to green roofs, it is  
198 merely an estimation of the largest realistic implementation of Green Roofs in Copenhagen, see Figure 6. For example,  
199 an investigation conducted by the municipality of Frederiksberg (Frederiksberg kommune 2011) identified the area



200 fraction of flat roofs in Frederiksberg suitable for installation of Green Roofs. This area fraction is used and scaled up to  
201 represent Copenhagen.

202

## 203 2.5. Functional unit

204 We compare Copenhagen in a business as usual scenario with scenarios where the various SCSs are implemented. The  
205 functional unit is to *Provide an urban area of 85,2 km<sup>2</sup> with a population of 664000 citizens for a duration of 1 year.*  
206 *The year investigated is 2013.* The functional unit is defined for an urban area and its population. However, the function  
207 of one urban area is by nature never identical to the function of another urban area. Though other urban areas can have  
208 similar population densities and similar size, the positioning properties of the system will be different, i.e. quality  
209 related positioning properties such as economic and social quality as well as more physical related properties such as  
210 access to supplying networks (water and electricity etc.). It is impossible to compare two urban areas, because they will  
211 never provide the same exact services. Therefore, the analysis is not used to compare one urban area to another urban  
212 area. Rather than comparing two different urban areas, our analysis compares the same urban system, with (slightly)  
213 different properties. As previously mentioned, we compare the urban system in its current state (reference scenario)  
214 with the same system where a SCS is implemented (GRo scenario, SWi scenario, PWC scenario, SWC scenario, SWM  
215 scenario, GRe scenario, SEG scenario). This type of assessment should yield an understanding of the influence of each  
216 SCS on the environmental performance of the city.

217

## 218 2.6. Assumption and limitations

219 We use UM-LCA for this assessment because UM-LCA can include embedded impacts. However, the approach still  
220 has limitations, that should be considered when the results of the UM-LCA are assessed. The UM-LCA is only useful  
221 with the right geographical boundaries and with the correct functional unit as discussed by Goldstein et al. (2013). This  
222 is because the urban-scale in the analysis might not be representing all the subsystems which affect the metabolic flows.  
223 Another issue is how stocks in the city is handled i.e. how the End of Life (EoL) of the stock is modelled. Stocks could  
224 for instance be building stocks, where the EoL is reached many years into the future. The final issue, not related to the  
225 choice of method or the modelling, is the limited data availability. It is not always possible to find sufficient, high  
226 quality data. In some situations, we have had to use alternative data and assumption to conduct the full assessment.  
227 The data for Copenhagen are mainly based on waste data. This means that the data does not account for the built-in  
228 delay in the metabolism, because products pile up in the urban system (also known as stock). For the energy, water,  
229 transport, and food consumption flows, the data are both site-specific (Copenhagen and Denmark) and time-specific

230 (2013). Data on raw material extraction, material production and assembly are general data from the Ecoinvent  
231 database. For each SCS, the data for metabolic savings (electricity, water, transport) when the SCS is implemented, is  
232 primarily from independent studies. Material consumption for each SCSs is obtained primarily from suppliers. All the  
233 data used, are aiming at covering the optimal geographical, technological, and temporal context and thus  
234 representativeness. However, there are limitations to the coverage; the geographical location for processes outside  
235 Copenhagen is unknown, while the metabolic entity and the EoL stage takes place in Copenhagen. The technology  
236 applied in the EoL stage happens in the future and is therefore also unknown. Thus, general data from the Ecoinvent  
237 database is used. World average is used when the location is unknown and site specific when the location is known. For  
238 the temporal coverage, everything is modelled as taking place in 2013. The model has been built around the  
239 Copenhagen waste statistics from 2013, and the consumption is extrapolated from this. However, in reality not all  
240 processes take place in 2013, but must have taken place before (e.g. production of the SCSs and related raw material  
241 extraction) and after (EoL for SCSs).  
242 This introduces an unknown level of uncertainty to the model, that cannot be addressed because the uncertainty for each  
243 piece of data is unknown (i.e. the temporal location of a given activity is not registered in the statistics). This  
244 uncertainty is, however, of limited importance. This is because even if we had the data on the actual temporal location  
245 of the individual activities, we would not have been able to address it in the product system model, due to the poor  
246 temporal resolution of the unit processes available from inventory databases.

247  
248

## 249 [2.7. Impact assessment method](#)

250 Characterizing LCI data into impact potentials which cover a range of impact categories can be done using several  
251 characterization methods. Here we use ReCiPe 2008 version 1.11 as the impact assessment method, which relies on the  
252 Hierarchist (H) perspective. The inventory data is initially classified to elementary flows and subsequently  
253 characterized to emissions both using the ReCiPe method. In GaBi there appears to be an error related to impact  
254 potentials belonging to Ionized Radiation amounting to a factor  $1,00000 \cdot 10^6$  (i.e. corresponding to a unit conversion  
255 error). This error has been corrected in the results. Weighting and aggregating of the results into a single score is not  
256 carried out, because weighting has no real effect on the results (Kalbar et al 2016) and hence the decision support value,  
257 and because ISO recommends not to use weighting in LCA's intended for public disclosure (ISO 2006b).  
258 The ReCiPe method provides a broad specter of midpoint impact categories, 18 categories in total. In this article, we  
259 provide results for the Global Warming potential (GWP) as the only midpoint category along with the three endpoint

260 categories; damage to human health, damage to resources, and damage to ecosystems. We have chosen the midpoint  
261 results for GWP as the only midpoint category to relate to, simply because of the significant focus on CO<sub>2</sub> emission  
262 (reduction) in society and at policy level in many cities knowing that this does comply to ISO-14040 (ISO 2006a).  
263 Copenhagen, in particularly, has a goal of becoming CO<sub>2</sub> neutral in 2025 (City Hall 2009), hence their sustainability  
264 goals are very much focused on CO<sub>2</sub>/climate change. All ReCiPe midpoint impact categories (see table 2) are calculated  
265 and presented in the supporting material.

266

### 267 3. Results

268 Figure 7 a) illustrates the estimated GWP from implementation of each of the seven SCSs in Copenhagen. The  
269 difference in the results between the reference scenario and the scenarios with the individual SCSs implemented are less  
270 than 1% for most of the SCSs. The GWP results reveal that 4 of the 7 solutions have a negative impact on the  
271 environmental performance of the urban system, and that most systems do not have a significant change in impact. The  
272 results for the endpoint categories presented in Figure 7 b), c) and d) generally exhibit the same tendency as the GWP  
273 midpoint results, thus indicating that the aggregated impact potentials follow the same tendency as the GWP midpoint.  
274 The main contributors to the impact potentials (obtained by hotspot and sensitivity analysis) are listed in Table 3.  
275 While the change in impact potential for the results shown in figure 7 a) to d) are shown and commented on in table 4.  
276 The impact potentials calculated with the individual SCSs implemented are generally lower compared to the reference  
277 scenario for the operation stage flows. It indicates that if the implementation is seen from a sole urban system operation  
278 point of view the SCSs have a positive impact on the environmental performance of the urban system. However, the  
279 impact potential trend changes when we include the embedded impacts of the material components needed to produce  
280 the SCSs. For other solutions, the operational stage flow is simply substituted with another operation stage flow, e.g. for  
281 the PWC, where transport is saved, but substituted with electricity use. A more detailed analysis of the results  
282 furthermore shows that the tendency when a new mechanical system is introduced is that the main contributor of  
283 impacts and damages is the materials needed for the mechanical system and hence the embedded impacts. For the SCSs  
284 that rely on ICT the components providing the ICT functionality (such as sensors and controllers) are the main  
285 contributors to the (embedded) impacts. The savings in consumption obtained when the SCS is implemented are  
286 observed in the operation stage flows within the urban system and hence the main contributors to the reduction of e.g.  
287 the GWP related impacts are the savings obtained by using the SCSs.

## 288 4. Discussion

289

### 290 4.1 Global Warming Potential

291 The GWP midpoint results show that an improvement of the environmental performance of Copenhagen is to be  
292 expected by adoption of SEG, SWMs, and SWC. Contrary, a decrease in environmental performance is to be expected  
293 by adoption of the remaining solutions. The results for the remaining ReCiPe midpoint categories are presented in the  
294 Supporting Information to this paper. The results of the remaining ReCiPe midpoint categories show in most cases the  
295 same tendencies as are observed for the GWPs. However, SWMs show a worsening of the performance of the urban  
296 system in 11 of the 18 categories and hence a general decrease of the environmental performance of the urban system,  
297 contrary to the results obtained for the GWPs. This indicates that even though the GWP is a generally accepted and  
298 used indicator for sustainability and environmental performance, it is considered advisable not to depend on this  
299 indicator solely, since this might result in burden shifting among impact indicators. Overall, SWMs have very little  
300 effect on the performance potential of the urban system. The relative urban system performance changes are very small  
301 when adopting SWMs. Not only in terms of GWP, but for all the impact categories. The same goes for GRO and SWC.  
302 The study shows that the three previously mentioned SCSs (SWMs, GROs and SWC) have no influence on the  
303 environmental performance of the urban system of Copenhagen. However, it should still be kept in mind that there may  
304 be a level of uncertainty associated with the results which is unknown. The impact reductions may very well be lower  
305 than the uncertainty, which we have not been able to quantify.

### 306 4.2 Endpoint

307 It is observed that the endpoint scores exhibit the same general trends as the GWP midpoint indicator when the damage  
308 potential expected from implementation of the SCSs is analyzed. It should be mentioned that the GWPs contribute to  
309 the endpoint indicators for human health and ecosystem damages. Even though the same general impact trends are  
310 observed for both the GWPs and the endpoint scores, there is a difference in the relative changes. For the SWi and the  
311 SEG the largest influences from the SCSs are found for the GWP, compared to the endpoint scores. Focusing only on  
312 the GWP, a more extreme picture in terms of environmental performance change for the SCSs is observed. For the  
313 other SCSs, the GWP is not more extreme than the endpoint scores, and hence the GWP exhibit the same the as the  
314 endpoint scores. From the impact potentials, both at midpoint level and the damage potential at endpoint level, it is  
315 possible to conclude that the only SCS that uniformly improves the environmental performance of Copenhagen is SEG.  
316 Judged across both midpoints and endpoints the environmental burden of Copenhagen appears uniformly to increase by  
317 adoption of the SWi, PWC, and GRE. Judged across both midpoints and endpoints the results are inconclusive for GRO,

318 SWC, and SWM. The reason the three last-mentioned SCSs (GRo, SWC and SWM) are inconclusive is due to the  
319 relative minute change influence on almost all the midpoint impacts categories. This influence is (very) small and  
320 taking the overall assessment uncertainty into account we claim that there is no clear tendency to whether the influence  
321 of implementation of these solutions will lead to a better or worse environmental performance of Copenhagen. In  
322 addition, since some midpoint impact categories indicate improvement, while others indicate worsening, the overall  
323 picture becomes inconclusive and dependent on weighing of the midpoint indicators. Because of this inconclusive  
324 picture and due to the uncertainties connected to this assessment method as such, it is not possible to conclude any  
325 clear/uniform tendency from these three SCSs.

326

### 327 4.3 Burden shifting

328 All solutions reduce impact potentials in operation stage, however, as discussed; most solutions increase the overall  
329 environmental burden of the urban system. This phenomenon is caused by a burden shift within the system, as can be  
330 seen from the results of the hotspot analysis shown in Table 3. The impacts are shifted from the operation stage to the  
331 raw material and production stages as illustrated in Figure 8. The burden is hence no longer mainly induced within the  
332 urban system as direct impacts, but rather embedded in the products/materials where the actual impact location is more  
333 uncertain. In some cases, larger impact shifts occur within the operation stage and hence within the urban system. This  
334 is in the cases where a SCS has high energy consumption. Here one operation stage reduction is substituted by an  
335 increase of another (i.e. energy/transport savings are substituted by a higher energy consumption). In such cases where a  
336 saving is substituted by increased consumptions, more of the major contributors for the total environmental impact  
337 occur in the urban system. By occurring in the urban system as a direct impact there is a greater chance that this kind of  
338 burden shift is accounted for.

339 The underlying problem with this burden shifting is an overestimate of real achieved CO<sub>2</sub> emissions reduction. For  
340 instance, the focus is on the reduction of direct impacts: building energy (both heat and electricity), transport, and  
341 household waste in the climate plan for Copenhagen (City Hall 2009). When we only focus on these direct impact  
342 reduction potentials, it is very likely that embedded impacts are forgotten or not accounted for. In the case of embedded  
343 impacts, the environmental burdens are not removed, but just moved from the city to a background system, which is not  
344 accounted for (properly). Based on the assessments conducted here one important issue emerges: great care should be  
345 taken when implementing SCSs to achieve environmental goals, as it is not necessarily certain that there are any  
346 environmental gains from implementing them, seen from the life cycle perspective where the entire value chain of SCS

347 is covered. If the assessments of the SCSs are limited to the direct impacts, it can look as though implementation may  
348 by a good idea and a step towards a sustainability goal. The general attention SCSs attract combined with the results  
349 presented in this paper highlights the importance of including the embedded impacts when assessing the environmental  
350 burdens of large system such as an urban system. Not only when we consider implementing SCSs, but also when we  
351 look at other types of urban system alterations.

352

#### 353 4.4 Copenhagen

354 In the assessment, we have also conducted a hotspot analysis of Copenhagen, to find the major drivers for the total  
355 environmental burden of Copenhagen without the implementation of any SCSs. The results of this can be seen in the  
356 Supporting Information to this paper. It is observed that the main contributors to urban system impacts are food  
357 consumption, consumption of electronics, mobility or transport, and construction activities. This is approximately the  
358 same results as found by Goldstein et al. analyzing five different cities (Goldstein et al 2013), except that Goldstein et  
359 al. (2013) found that a main contributor is building energy and not electronics consumption as found in our analysis.  
360 The reason why building energy has been included in our study is that some of the SCSs are intended to reduce  
361 consumption hereof. Since Copenhagen differs from cities analyzed by Goldstein et al. especially in terms of embedded  
362 impacts of specific flows, the deviation in the main contributors for the environmental burden, seems valid. A reason  
363 why the building energy is not a main contributor in Copenhagen, while the literature suggest that it is a main  
364 contributor for other cities around the world, may be that there has been a large focus in recent years on greening of the  
365 energy grid and on reducing electricity and heating needs in buildings, amongst others through better insulated  
366 buildings. Because a considerable fraction of the energy system in Denmark consists of renewable energy sources, the  
367 energy supply of Copenhagen is consequently less dependent on fossil fuels. The building energy in Copenhagen  
368 therefore contributes to less of an impact potential than the cities assessed in Goldstein et al. (2016). From the main  
369 contributors found in our analysis, it is evident that none of the SCSs have (significant) saving influence on any of the  
370 metabolic flows that are considered the main impact contributors. At the same time the SCSs contribute to an increase  
371 in the consumption of electronics, which is a major contributor for the total environmental burden of Copenhagen.  
372 Thereby it could be beneficial to do further work assessing SCSs that are focused on savings of the metabolic flows that  
373 are major contributors for the environmental burden of Copenhagen.

374 The fact that building energy is a main contributor for the total environmental burden for other cities than Copenhagen  
375 highlight the point that it might be beneficial for the entire understanding of the SCSs influence on urban systems to

376 implement them in various types of cities, which have different major impact contributors. Furthermore, it would be  
377 interesting to analyze whether some of the SCSs would perform different/better under other climatic conditions than the  
378 Danish.

379

#### 380 4.5 The scale of the analysis

381 The change in impact potentials for Copenhagen induced by the SCSs is calculated and shows that the changes for most  
382 SCSs are quite small. This is because the (urban) system of Copenhagen is very large, and the changes induced by a  
383 SCS is not significant in comparison to the entire urban system. In other words; the potential of the SCSs is not grand.  
384 Even though the impact changes from an SCS implementation is small; it might be that if one of the SCSs is  
385 implemented in Copenhagen in real life, the resulting changes could be even smaller. This is because our assessment  
386 assumes a 100 % implementation of SCSs in Copenhagen, which might not be a realistic scenario. Nevertheless, the  
387 100 % implementation scenarios provide an estimate of the maximum expectable benefit from an SCS implementation.  
388 We consider the SWi as an example. In this scenario, it is assumed that all windows in commercial buildings are  
389 changed or altered to include the electrochromic film (ITO material). As is obvious to most readers; there are other (also  
390 “unsmart”) kinds of window shading solutions available, both for internal and external shading which provide the same  
391 service as the SWi and many commercial buildings might already have such an (“unsmart”) shading system. Because  
392 alternatives may already be installed it is unlikely that a 100% implementation could happen, which once again  
393 highlight that our calculations are to be regarded as maximum expected benefit.

#### 394 4.6 Limited number of Smart City Solutions

395 A limited number of SCSs are assessed. The scenarios indicate that SCS adoption is not necessarily to the benefit of  
396 environmental sustainability performance of an urban system, even though a SCS might appear beneficial from the  
397 direct saving potentials. However, the tendency observed from our results is not convincing enough to give a general  
398 environmental sustainability picture of SCSs given that some of the solutions show improvement and that the impact on  
399 the environmental performance of city in some cases is very small. As indicated by the hotspot and sensitivity analysis  
400 in Table 3, there are certain parameters for each SCS that largely controls the environmental burden of the assessed  
401 SCSs. Hence, a reduction of such parameters and/or a significant urban system flow saving when implemented, could  
402 contribute to a different picture on SCSs than the picture emerging from our assessment. Focal points in the  
403 sustainability refinement of the SCSs could be: careful examination of when and where it is necessary to use ICT  
404 components, especially if the savings from operation are of limited proportions. Such basic assessments are relevant

405 because our hotspot analysis revealed that the ICT (e.g. sensor, controller) components are hotspots for some of the  
406 SCSs. And for most SCSs, it is possible to remove the ICT components from the solutions and still have the SCSs  
407 provide the same service. Another focal point is minimization of the electricity consumption (in our case relevant for  
408 PWC and GRe), and finally reducing the general material consumption, especially for the materials that are based on  
409 scarce resources. Another issue worth considering is the possibility of making the SCSs repairable, because the ICT  
410 components, if broken, are usually replaced instead of repaired.

411 Even though the SCSs save consumption, of for instance electricity, and claim to improve the sustainability  
412 performance of an urban system, the solutions are not necessarily implemented with the purpose of reducing the  
413 environmental impact. The purpose of an SCS implementation could also be other improvements of the urban systems,  
414 such as improved comfort from using SWis, reducing traffic from waste collection, or better water management in cities  
415 to reduce overload of existing sewer network from GRo. In other words, motivation of the implementation could hence  
416 be on social or economic aspects of the urban system. However, these aspects are not part of our assessment, and we  
417 can therefore not say anything about the SCSs performance on these indicators. These benefits could be assessed in  
418 future work. The fact that there can be other motives than potential environmental gains for implementing the SCSs,  
419 only highlights the importance of transparent communication of motives for implementing SCSs.

## 420 5. Conclusions

421 This study has tested the influence that seven different Smart City Solutions (SCSs) have on an urban system in a UM-  
422 LCA perspective. The urban system investigated is Copenhagen. It is found that only one of the SCSs reduce the  
423 environmental burden of Copenhagen; the SEG. The solutions SWi, PWC and GRe are found to increase the  
424 environmental burden of Copenhagen, while the results for the solutions GRo, SWC and SWMs are inconclusive,  
425 because the influences they have on Copenhagen are overshadowed by uncertainties in the model. This illustrates, that  
426 the SCSs analyzed here have limited ability to alter the environmental sustainability performance of an urban system in  
427 a positive direction. The limited positive influence from the SCSs is due to burden shifting from the direct impacts of  
428 the urban system to embedded impacts which are out of sight for most policy makers. At the same time, the savings in  
429 metabolic flows that the SCSs provide, are not necessarily on the exact flows that are major contributors to the  
430 sustainability performance of Copenhagen. This lack of focus on impact contribution might be why the assessed SCSs  
431 do not improve the performance of Copenhagen. Even though the beneficial influence of the SCSs is limited, there are  
432 still not sufficient results to discard the idea of using the implementation of SCSs to reduce an urban system's



433 environmental burden. Further work on altering/designing the SCSs so they use less material and less ICT, testing of the  
434 influence of other solutions, and testing of the influence on other cities could be conducted.

## 435 References

- 436 Baetens R, Jelle BP, Gustavsen A (2010) Properties, requirements and possibilities of smart windows for dynamic  
437 daylight and solar energy control in buildings: A state-of-the-art review. *Sol Energy Mater Sol Cells* 94:87–105.  
438 <http://dx.doi.org/10.1016/j.solmat.2009.08.021>
- 439 Bakıcı T, Almirall E, Wareham J (2013) A Smart City Initiative: The Case of Barcelona. *J of the knowl econ.* 4: 135-  
440 148. <http://doi.org/10.1007/s13132-012-0084-9>
- 441 Bianchini F, Hewage K (2012) How “green” are the green roofs? Lifecycle analysis of green roof materials. *Build*  
442 *Environ.* 48:57–65. <http://dx.doi.org/10.1016/j.buildenv.2011.08.019>
- 443 Britton TC, Stewart RA, O’Halloran KR (2013) Smart metering: Enabler for rapid and effective post meter leakage  
444 identification and water loss management. *J Clean Prod.* 54:166–76. <http://dx.doi.org/10.1016/j.jclepro.2013.05.018>
- 445 Cocchia A (2014) Smart and Digital City: A systematic Literature Review. In Dameri, R.P and Rosenthal-Sabroux C.  
446 (eds) *Smart City*. Springer, Switzerland, pp 13-43
- 447 Chou J-S and Ngo N-T (2016) Smart grid data analytics framework for increasing energy savings in residential  
448 buildings. *Autom Constr* 72:247-257. <http://www.sciencedirect.com/science/article/pii/S0926580516000030>
- 449 City Hall (2009) Carbon Neutral by 2025 – Copenhagen Climate plan. City of Copenhagen, The Technical and  
450 Environmental Administration, City Hall. <https://www.energycommunity.org/documents/copenhagen.pdf>
- 451 Danmarks statistik (2013) Folketal den 1. i kvartalet efter køn, alder, civilstand, område og tid. Danmarks statistik  
452 <http://www.statistikbanken.dk/statbank5a/selectvarval/saveselections.asp>. Accessed 30 November 2016
- 453 Danmarks statistik (2016) Areal efter område og tid. Danmarks statistik  
454 <http://www.statistikbanken.dk/statbank5a/selectvarval/saveselections.asp>. Accessed 30 November 2016
- 455 Dansk skraldesug ApS (2016) Minimax. Dansk skraldesug ApS.  
456 <http://www.danskskraldesug.dk/Webnodes/da/Web/Dansk+Skraldesug/Affaldssystemer/Minimax++%28fuldt+nedgrav>  
457 [et%29](http://www.danskskraldesug.dk/Webnodes/da/Web/Dansk+Skraldesug/Affaldssystemer/Minimax++%28fuldt+nedgrav). Accessed 30 November 2016
- 458 EcoGrid EU (2016) EcoGrid EU - A Prototype for European Smart Grids. Deliverable D6.7 Overall evaluation and  
459 conclusion. EcoGrid EU. <http://www.eu-ecogrid.net>. Accessed 30 November 2016
- 460 Enevo (2016) Products. Enevo. <http://www.enevo.com/products/>. Accessed 30 November 2016
- 461 Envac ab (2009) Vakuumteknologi. Envac. [http://www.envac.dk/produkter-ydelser/vores-teknik/teknologien-bag-](http://www.envac.dk/produkter-ydelser/vores-teknik/teknologien-bag-affaldssug)  
462 [affaldssug](http://www.envac.dk/produkter-ydelser/vores-teknik/teknologien-bag-affaldssug). Accessed 30 November 2016
- 463 European Commission (2010) International Reference Life Cycle Data System (ILCD) Handbook --  
464 General guide for Life Cycle Assessment -- Detailed guidance. Publication Office of the European Union, Luxembourg  
465 <http://lct.jrc.ec.europa.eu/pdf-directory/ILCD-Handbook-General-guide-for-LCA-DETAIL-online-12March2010.pdf>
- 466 ISO (2006a) ISO 14040:2006 - Environmental management – Life cycle assessment – Principles and Framework.  
467 International Standards Organization, Switzerland

- 468 ISO (2006b) ISO 14044:2006 - Environmental management – Life cycle assessment – Requirements and guidelines.  
469 International Standards Organization, Switzerland
- 470 Frederiksberg kommune (2011) Analyse for potentialet for grønne tage, solceller og tagvindmøller. Frederiksberg  
471 kommune. <https://www.frederiksberg.dk/sites/default/files/meetings-appendices/E58F7213-982F-483D-93C5-9C2EBA08C2DE/2251635-2329574-1.PDF>. Accessed 30 November 2016
- 473 Free ES, Selkowitz SE, Clear RD, DiBarolomeo DL, Klems JH, Fernandes LL, Ward GJ, Inkarojrit V and Yazdanian  
474 M (2006) A Design Guide for Early-Market Electrochromic Windows. Lawrence Berkeley Natl Lab  
475 <http://escholarship.org/uc/item/3mm8j7q1%0ACopyright>. Accessed 30 November 2016
- 476 Gutierrez JM, Jensen M, Henius M and Riaz T (2015) Smart Waste Collection System Based on Location Intelligence.  
477 *Procedia Comput Sci* 61:120–7. <http://dx.doi.org/10.1016/j.procs.2015.09.170>
- 478 Goldstein B, Hauschild M, Fernández J, Birkved M (2016) Testing the environmental performance of urban agriculture  
479 as food supply in northern climates. *J Clean Prod* 135:984-94
- 480 Goldstein B, Birkved M, Quitzau M-B, Hauschild M (2013) Quantification of urban metabolism through coupling with  
481 the life cycle assessment framework: concept development and case study. *Environ Res Lett* 8 35024
- 482 Hauber-Davidson G, Idris E (2006) Smart Water Metering. *Water* 33.3: 38-41
- 483 Hu Z, Li C, Cao Y, Fang B, He L and Zhang M (2014) How smart grid contributes to energy sustainability. *Energy*  
484 *Procedia* 61:858–61 <http://dx.doi.org/10.1016/j.egypro.2014.11.982>
- 485 ITU, International Telecommunication Union (2014) Smart water management in cities. International  
486 Telecommunication Union. [https://www.itu.int/en/ITU-T/focusgroups/ssc/Documents/Approved\\_Deliverables/TR-SWM-cities.docx](https://www.itu.int/en/ITU-T/focusgroups/ssc/Documents/Approved_Deliverables/TR-SWM-cities.docx) Accessed 30 November 2016
- 488 Jefferson B, Laine a, Parsons S, Stephenson T and Judd S (2000) Technologies for domestic wastewater recycling.  
489 *Urban Water* 1:285–92
- 490 Joss S, Molella A (2013) The Eco-City as Urban Technology: Perspectives on Caofeidian International Eco-City  
491 (China). *J of urban technology* 20: 115-137. <http://doi.org/10.1080/10630732.2012.735411>
- 492 Kalbar P, Birkved M, Nygaard S, Hauschild M (2016) Weighting and Aggregation in Life Cycle  
493 Assessment: Do Present Aggregated Single Scores Provide Correct Decision Support? *J Ind*  
494 *Ecol* 0:1–10 Online: <http://doi.wiley.com/10.1111/jieec.12520><sup>[1]</sup><sub>SEP</sub>
- 495 Kamstrup (2015) Data sheet Siemens MAG 8000 with READy Gateway. Kamstrup. <http://products.kamstrup.com/>.  
496 Accessed 30 November 2016
- 497 Kamstrup (2016a) Non-Revenue Water – understanding and working proactively with Non-Revenue Water. Kamstrup.  
498 <https://www.kamstrup.com/en-en/business-areas/water-metering/non-revenue-water>. Accessed 30 November 2016
- 499 Kamstrup, (2016b), The digital water utility - white paper on the potential of smart metering. Kamstrup.  
500 <https://www.kamstrup.com/en-uk/business-areas/water-metering/the-digital-water-utility>. Accessed 30 November 2016
- 501 Kennedy C, Pincetl S, Bunje P (2011) The study of urban metabolism and its applications to urban planning and design.  
502 *Environ Pollut* 167:184–185. <http://dx.doi.org/10.1016/j.envpol.2010.10.022>
- 503 Larsen H, Petersen L (2011) Risø Energy Report 10 : Energy for smart cities in an urbanised world. Danmarks  
504 Tekniske Universitet, Risø Nationallaboratoriet for Bæredygtig Energi. [http://orbit.dtu.dk/en/publications/risoe-energy-report-10--energy-for-smart-cities-in-an-urbanised-world\(4e125ec3-2089-483b-a1bf-4840807be6b1\).html](http://orbit.dtu.dk/en/publications/risoe-energy-report-10--energy-for-smart-cities-in-an-urbanised-world(4e125ec3-2089-483b-a1bf-4840807be6b1).html). Accessed 30  
505 November 2016

- 507 Lazarova V, Hills S, Birks R (2003) Using recycled water for non-potable, urban uses: A review with particular  
508 reference to toilet flushing. *Water Sci Technol: Water Supply* 3:69–77
- 509 Malik AS, Bouzguenda M (2013) Effects of smart grid technologies on capacity and energy savings - A case study of  
510 Oman. *Energy* 54:365–371. <http://dx.doi.org/10.1016/j.energy.2013.03.025>
- 511 Mamun MAA, Hannan MA, Hussain A, Basri H (2014) Real Time Bin Status Monitoring for Solid Waste Collection  
512 Route Optimization. *Eng Technonogy*. <http://doi.org/10.1049/cp.2014.1077>
- 513 Memon FA, Zheng Z, Butler D, Shirley-Smith C, Lui S, Makropoulos C, Avery L (2007) Life cycle impact assessment  
514 of greywater recycling technologies for new developments. *Environ Monit Assess* 129:27–35
- 515 Nam T, Pardo TA (2011) Conceptualizing smart city with dimensions of technology, people, and institutions. *Proc 12th*  
516 *Annu Int Digit Gov Res Conf Digit Gov Innov Challenging Times*. <http://doi.org/10.1145/2037556.2037602>
- 517 Neirotti P, De Marco A, Cagliano AC, Mangano G, Scorrano F (2014) Current trends in smart city initiatives: Some  
518 stylised facts. *Cities* 38:25–36. <http://dx.doi.org/10.1016/j.cities.2013.12.010>
- 519 Niachou A, Papakonstantinou K, Santamouris M, Tsangrassoulis A, Mihalakakou G (2001) Analysis of the green roof  
520 thermal properties and investigation of its energy performance. *Energy Build* 33:719–729
- 521 Opti (2014) Advanced Green Roof Retrofit SAP North America Newtown Square, Pennsylvania. OptiRTC, Inc.  
522 [https://d1qmdf3vop2107.cloudfront.net/turquoise-](https://d1qmdf3vop2107.cloudfront.net/turquoise-tomato1.cloudvent.net/compressed/d6a9811cca9cf498b7ac09ea692dc5d.pdf)  
523 [tomato1.cloudvent.net/compressed/d6a9811cca9cf498b7ac09ea692dc5d.pdf](https://d1qmdf3vop2107.cloudfront.net/tomato1.cloudvent.net/compressed/d6a9811cca9cf498b7ac09ea692dc5d.pdf). Accessed 30 November 2016
- 524 Optigreen (2011) Technical Brochure Green Roofs. Optigrün.  
525 [https://www.optigruen.de/fileadmin/contents/sprache\\_englisch\\_uk/Blaetterkatalog/index.html](https://www.optigruen.de/fileadmin/contents/sprache_englisch_uk/Blaetterkatalog/index.html). Accessed 30 November  
526 2016
- 527 Pincetl S, Bunje P, Holmes T (2012) An expanded urban metabolism method: Toward a systems approach for assessing  
528 urban energy processes and causes. *Landsc Urban Plan* 107:193–202.  
529 <http://dx.doi.org/10.1016/j.landurbplan.2012.06.006>
- 530 Punkkinen H, Merta E, Teerioja N, Moliis K, Kuvaja E (2012) Environmental sustainability comparison of a  
531 hypothetical pneumatic waste collection system and a door-to-door system. *Waste Management*. 32: 1775-1781.  
532 <http://dx.doi.org/10.1016/j.wasman.2012.05.003>
- 533 Rovetta A, Xiumin F, Vicentini F, Minghua Z, Giusti A, Qichang H (2009) Early detection and evaluation of waste  
534 through sensorized containers for a collection monitoring application. *Waste Manag* 29:39–49.  
535 <http://dx.doi.org/10.1016/j.wasman.2009.08.016>
- 536 Teerioja N, Moliis K, Kuvaja E, Ollikainen M, Punkkinen H, Merta E (2012) Pneumatic vs. door-to-door waste  
537 collection systems in existing urban areas: A comparison of economic performance. *Waste Manag* 32:1782–1791.  
538 <http://dx.doi.org/10.1016/j.wasman.2012.05.027>
- 539 Townsend A (2013) SMART CITIES - Big data, civic hackers and the quest for a new utopia. W. W. Norton, New  
540 York.
- 541 VanWoert ND, Rowe DB, Andresen JA, Rugh CL, Xiao L (2005) Green roof stormwater retention: Effects of roof  
542 surface, slope and media depth. *J Environ Qual* 40:659–664. <http://dx.doi.org/10.2134/jeq2004.0364>
- 543 View Dynamic Glass. Product Guide. View. <https://viewglass.com/assets/pdfs/product-guide.pdf>. Accessed 30  
544 November 2016

- 545 View Dynamic Glass (2010) Energy benefits of View Dynamic Glass in workplaces. View.  
546 <https://viewglass.com/assets/pdfs/workplace-white-paper.pdf>. Accessed 30 November 2016
- 547 Villareal E, Dixon A (2005) Analysis of a rainwater collection system for domestic water supply in Ringdansen,  
548 Norrköping, Sweden. *Build and environ* 40: 1174-1184. <http://doi.org/10.1016/j.buildenv.2004.10.018>
- 549 Yang J, Yu Q, Gong P (2008) Quantifying air pollution removal by green roofs in Chicago. *Atmos Environ* 42:7266–  
550 7273
- 551 Zadeh SM, Hunt DVL, Lombardi DR, Rogers CDF (2013) Shared urban greywater recycling systems: Water resource  
552 savings and economic investment. *Sustain* 5:2887–2912

## 553 Tables

554 **Table 1** The seven Smart City Solutions assessed in this study. The Solutions represent a broad number of domains  
555 within the building and ICT scope. The four domains represented are the building, waste, water and power domain.

Solutions	Dedicated urban solution	Description	Sources
<b>Building Domain</b>			
<b>Green Roofs (GRo)</b>	No	Roofing layer on flat roofs consisting of a plant layer and retention layer, that can be automatically controlled. The retained water can be stored in tanks and later used for purposes where non-drinking quality is required. Results in <b>reduction of water use</b> and <b>reducing air pollution</b> is due to the plant materials. Requires installation of new mechanical system.	(Optigreen 2011; Opti 2014; Bianchini et al 2012; Niachou et al 2001; VanWoert et al 2005; Yang et al 2008)
<b>Smart Windows (SWi)</b>	No	A thin optical change film is installed in the windows on commercial buildings. The film change by a voltage impulse, connected to a manual and automatic control system. Resulting in <b>electricity reduction</b> on air-conditioning and lighting, <b>increasing energy use</b> for heating. Requires installation of new mechanical system.	(View Dynamic Glass n.d., 2010; Baetens et al 2010; Free et al 2006)
<b>Waste Domain</b>			
<b>Sensorized Waste Collection (SWC)</b>	No	The amount of waste in the garbage cans are measured by sensors. The plan for the garbage trucks to empty the cans is made based in the measurements. Resulting in a <b>reduction in transport</b> for waste collection. Does not require installation of new mechanical system.	(Enevo 2016; Mamun et al 2014; Rovetta et al 2009; Gutierrez et al 2015)
<b>Pneumatic Waste Collection (PWC)</b>	Yes	Waste is transported by vacuum trough an underground piping system to a collection terminal. The system is automatically controlled, when the level waste in the inlets reach a certain level. Resulting in a <b>reduction in transport</b> of waste. Requires installation of new mechanical system.	(Teerioja et al 2012; Dansk skraldesug Aps 2016; Envac ab 2009)
<b>Water Domain</b>			
<b>Greywater Recycling (GRe)</b>	Yes	Water from showers, wash basins etc. is collected in an extra loop, cleaned and reused for purposes that requires non-drinking quality water. The ICT make sharing of water between residential and commercial buildings possible. Results in <b>reduction of water use</b> . Does not require installation of new mechanical system.	(Memon et al 2007; Zadeh et al 2013; Jefferson et al 2000; Lazarova et al 2003)

<b>Smart Water Meters (SWM)</b>	No	Smart meters, receiving data from sensors connected to the water piping system and accessing old data, is connected to the water piping system. Now being able to detect leaks and make the consumers aware of their water consumption. Resulting in a <b>water reduction</b> , due to reduced leakage, and an <b>electricity reduction</b> due to the reduced amount of transported water. Does not require installation of new mechanical system.	(Britton et al 2013; ITU 2014; Kamstrup 2016a, 2016b; Hauber-Davidson et al 2006)
<b>Power Domain</b>			
<b>Smart Energy Grid (SEG)</b>	No	Smart meters, receiving data from heat sensors in the building, control the heating based on availability of electricity as well as the heating settings. The consumers are at the same time made aware of the consumption. Resulting in a <b>reduction in electricity use</b> and an <b>electricity shift</b> from coal produced to wind produced electricity. Does not require installation of new mechanical system.	(EcoGrid EU 2016; Hu et al 2014; Malik et al 2013; Chou et al 2016)

556

557 **Table 2** The included impact categories, when the ReCiPe impact assessment method is used. For water depletion,  
558 however, normalizations factors are all zero. Normalized and endpoint impact potentials for water depletion are  
559 therefore not included in results. Results for Endpoint Damage and the midpoint category GWP is shown in the article.  
560 Remaining results can be seen in supporting material.

Midpoint impact categories		Endpoint categories
Agricultural land occupation potential	Metal depletion potential	Damage to human health Damage to ecosystems diversity Damage to resources availability
Global warming potential	Natural land transformation potential	
Fossil depletion potential	Ozone depletion potential	
Freshwater ecotoxicity potential	Particulate matter formation potential	
Freshwater Eutrophication potential	Terrestrial acidification potential	
Human Toxicity potential	Terrestrial ecotoxicity potential	
Ionizing radiation potential	Urban land occupation potential	
Marine ecotoxicity potential	Water depletion potential	
Marine eutrophication potential		

561

562 **Table 3** Main contributors to the impact potentials for the different Smart City Solutions. The parameters are based on  
563 hotspot and sensitivity analysis, conducted on all midpoint impact categories available when using ReCiPe. The stage of  
564 the parameter is indicated as either raw material and production stage or operation stage. The red color indicates that the  
565 parameter increase impact potential, while the green color indicates a reduction of impact potential. Parameters  
566 generally show reduction of impact potentials in operation stage, but increase in impacts in production stage.

Smart City Solution	Raw Material and Production Stage Flows	Operation Stage Flows
<b>Green Roofs (GRo)</b>	Soil, Plastic, & PVC Avoided Heat from PVC Incineration & Soil Reuse	
<b>Smart Windows (SWi)</b>	ITO	Avoided Electricity Use
<b>Sensorized Waste Collection (SWC)</b>	Sensor & Controller	Avoided Transport
<b>Pneumatic Waste Collection (PWC)</b>		Electricity Use Avoided Transport

Greywater Recycling (GRe)		Electricity Use
Smart Water Meters (SWM)	Sensor & Controller	Avoided Electricity Use
Smart Energy Grid (SEG)	Internet Access & Sensor	Avoided Electricity Use & Avoided electricity produced by coal

567

568

569

570

**Table 4** The relative change in impact potential for characterized midpoint category GWP and for the change in impact potential for the characterized endpoint categories damage to: Human Health, Resources, and Ecosystem. Negative change means that performance is improved from implementation of SCS.

Solutions	Environmental Performance for Copenhagen		Comment
	Global Warming Potential (GWP)	Endpoint Damage	
<b>GRo</b>	+ 0,084%	Smaller than +0,5% for all categories	The main contributors to the impact potentials originate from materials use e.g. soil and plastic needed for the mechanical construction. Avoided/mitigated air pollution and water savings only compensate for the material use to a limited degree.
<b>SWi</b>	+ 75%	+ 70% for Human Health + 42% for Resources and + 46% for Ecosystem	The main contributor to impacts potentials is Use of ITO between glazing. The material is of metallic origin, relying on scarce resources. The reduction of the electricity consumption only has very limited compensatory impacts compared to the ITO material induced impacts.
<b>SWC</b>	- 0,17%	-0,1%	The main contributors to the impact potentials are sensors and controllers, which both increase the induced impacts, but no more than compensatory impacts obtained from avoided transport.
<b>PWC</b>	+ 0,76%	+ 1% for Resources and smaller than + 1% for Human Health and Ecosystem	Electricity consumption to pneumatic pumps during operation are the dominating contributor to the impacts potentials. This electricity consumption induced impacts largely outweighs the savings from avoided transport.
<b>GRe</b>	+ 0,70%	+ 1% for Resources and smaller than 1% for Human Health and Ecosystem	Electricity use during operation for the water pumps is the main contributor to the impact potentials. This electricity consumption induced impacts largely outweighs the savings from avoided water use.
<b>SWM</b>	- 0,024%	Smaller than + 0,1% for Human Health and Resources, and smaller than -0,1 for Ecosystem	Indicates that midpoint impact potentials only exhibit performance improvement in some categories. Main contributors to induced impacts are sensors and controllers, while avoided electricity use accounts for the avoided impacts.
<b>SEG</b>	- 10%	- 4,8% for Human Health - 3,0% for Resources and - 9,0% for Ecosystem	The main contributor to avoided impacts potentials is the reduced electricity consumption while internet access component increase accounts for the majority

---

of the induced impacts. The reduced electricity consumption outweighs the use of material use.

---

571

572

## 573 Figure Captions

574

575 **Figure 1** The Geographical scope of the analysis: The municipality of Copenhagen and Frederiksberg, marked with  
576 grey.

577

578 **Figure 2** The metabolic flows used as input for the operation stage in the UM-LCA. The figure is inspired from  
579 (Goldstein et al. 2013).

580

581 **Figure 3** A City UM-LCA model. The stage methodology from LCA adds to the typical UM of cities to give a more  
582 complete picture of the city's impact potential. The metabolic flows work as input for the operation stage and the  
583 metabolic fates work as input for the EoL stage. The figure is inspired from (Goldstein et al. 2013).

584

585 **Figure 4** The UM-LCA model for the Smart City Solutions. The modelling of the Smart City Solution is made like a  
586 product LCA. Using material compositions and use data as input.

587

588 **Figure 5** Illustration of the system boundaries for Copenhagen and the Smart City Solutions modelling. The direct and  
589 embedded impacts excluded from the system is marked with red, while the direct impacts included marked with black  
590 and the embedded impacts included is marked with blue.

591

592 **Figure 6** An example of the "100% implementation" of the Smart City Solution for Green Roofs. The results for Green  
593 Roof implementation are scaled from an investigation of a smaller area in Copenhagen (Municipal of Frederiksberg),  
594 and represents the complete, but realistic implementation of a solution in the urban area.

595

596 **Figure 7** Characterized midpoint results for a) GWP [kg CO<sub>2</sub>-eq.] calculated using ReCiPe 2008 v. 1.11 Hierarchist.  
597 Characterized endpoint results calculated using ReCiPe 2008 v. 1.11 Hierarchist. The endpoints include b) Human  
598 Health [DALY], c) Resources [\$], and d) Ecosystems [Species yr.]. The results are for the reference scenario of

599 Copenhagen and for the scenarios where Smart City Solutions are introduced individually. Results are calculated for the  
600 year 2013.

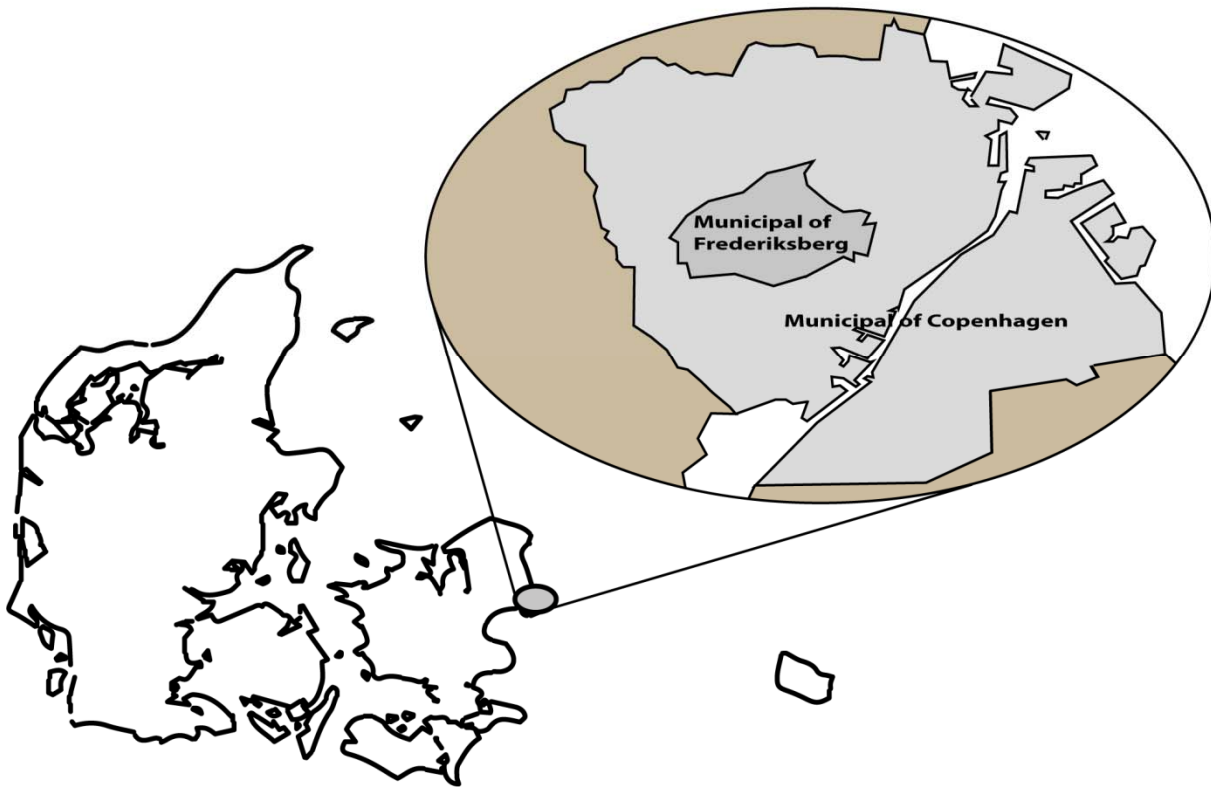
601

602 **Figure 8** Illustrating the burden shifting that happens when implementing Smart City Solutions in Copenhagen. The  
603 illustration of the change in size of the burden is not in scale to the calculated impact potential.

604

## 605 Figures

606 Figure 1:



607

608

609 Figure 2:



# METABOLIC FLOWS

**Food:** vegetables, fruits, juice, meat, fish, eggs, dairy, grains, sugar, tea, coffee, cigarettes, alcoholic beverage

**Water:** residential, commercial, industrial

**Transport:** private (car, motorcycle, cycle), public (train, bus), freight (train, lorry)

**Building energy:** electricity, thermal energy (heating), oil and gas

**Metals:** steel, iron, aluminum, precious metals

**Plastics:** polyvinylchloride, mixed plastic

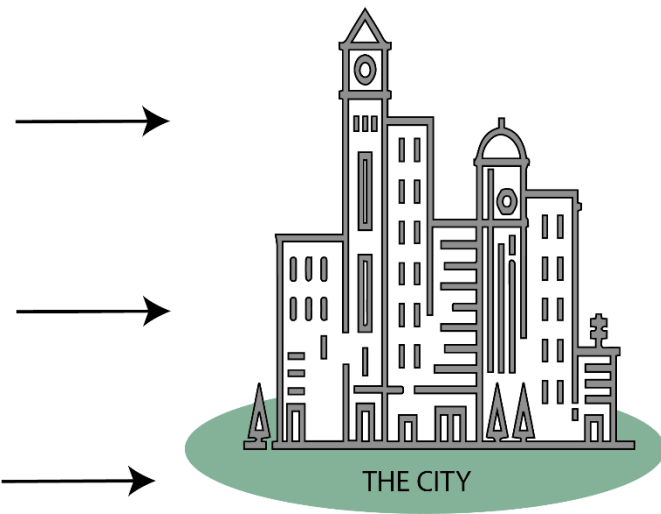
**Paper:** newsprint, cardboard

**Glass:** white/clear, green, brown (all packaging)

**Rubber:** natural, synthetic

**Electronics:** white goods (stove, fridges etc.), consumer electronics (laptops, tv's etc.), batteries, PV-panels

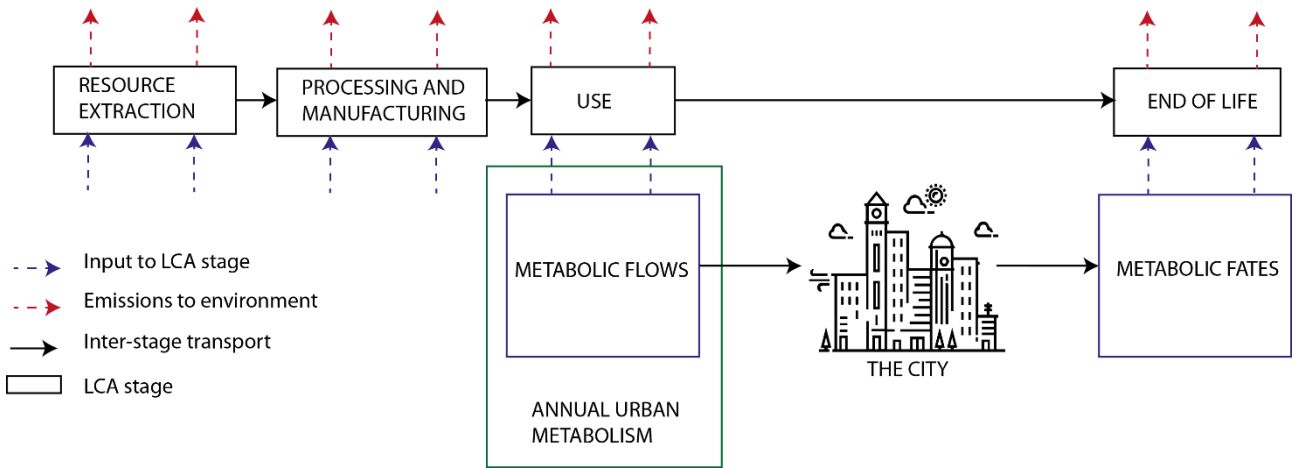
**Construction materials:** concrete, wood, bricks, plastics, steel, processed fibre products, windows, insulation



610

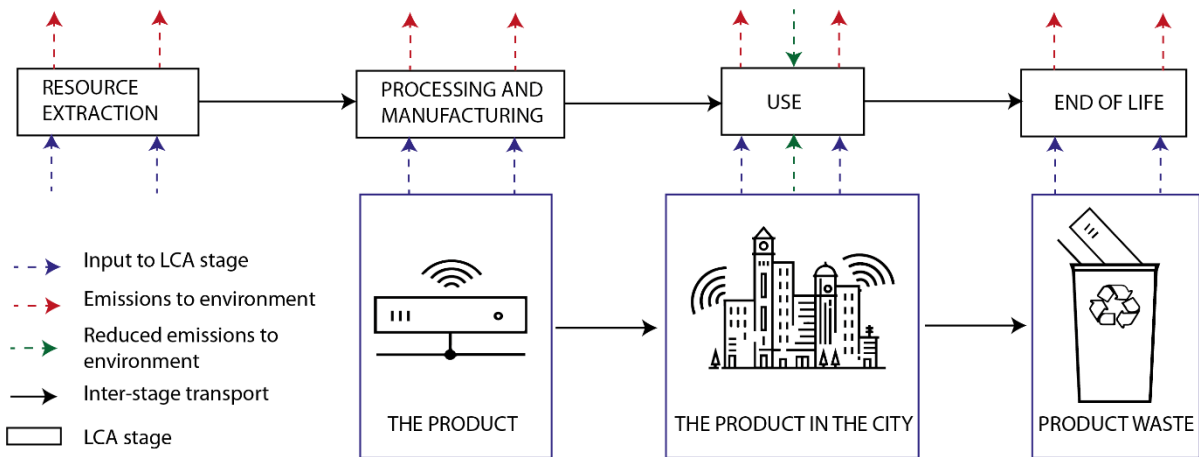
611 Figure 3:

612



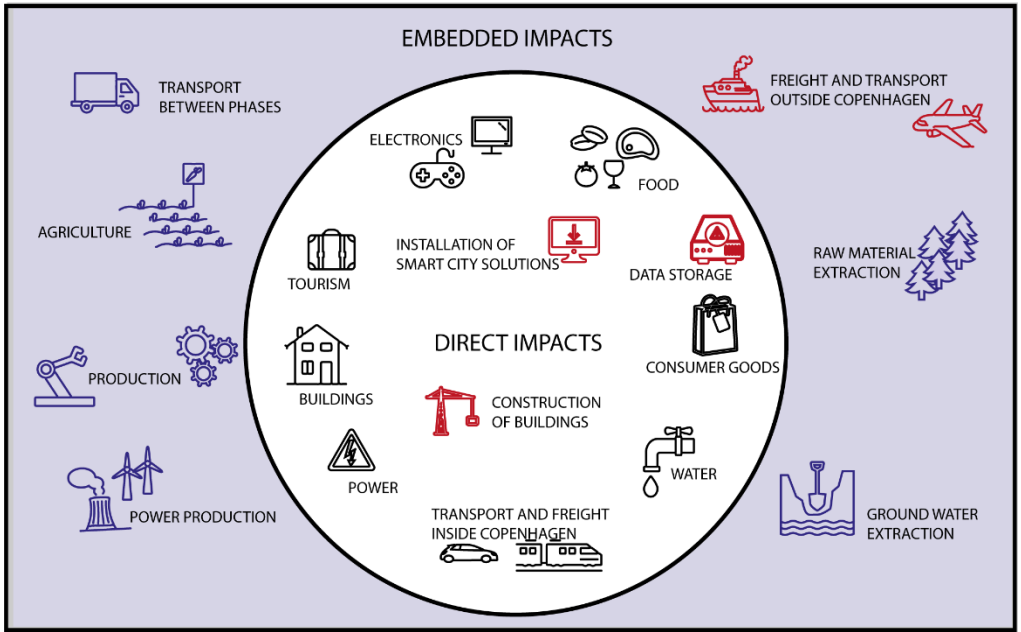
613

614 Figure 4:



615

616 Figure 5:



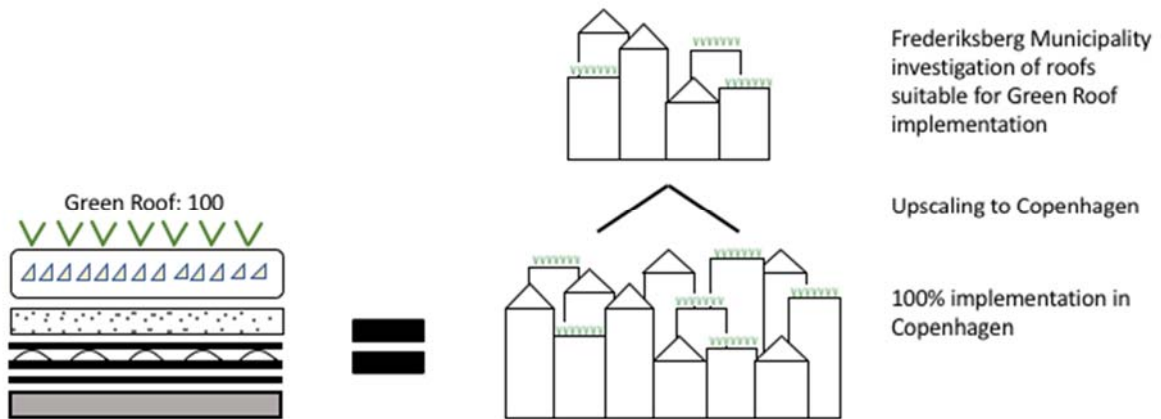
617

618

619

620

Figure 6:

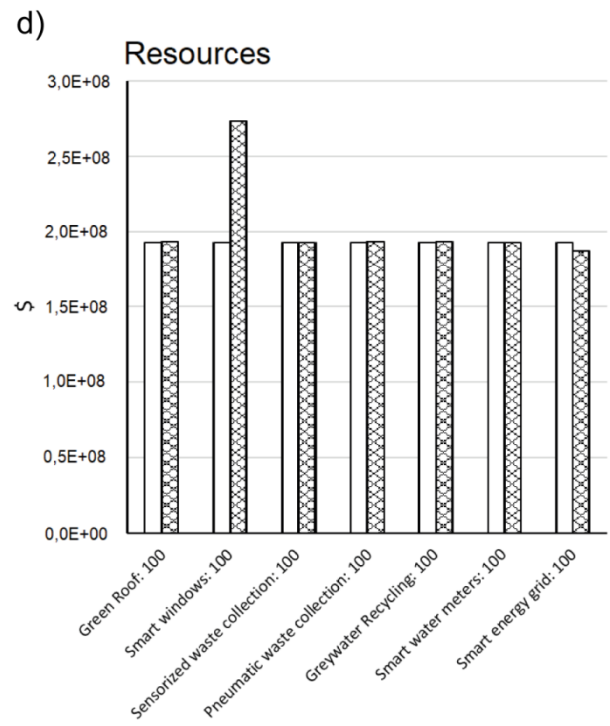
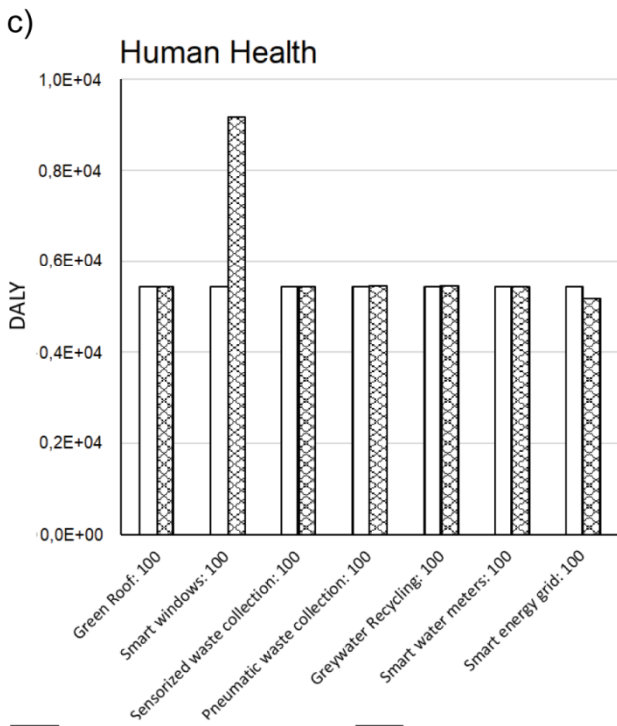
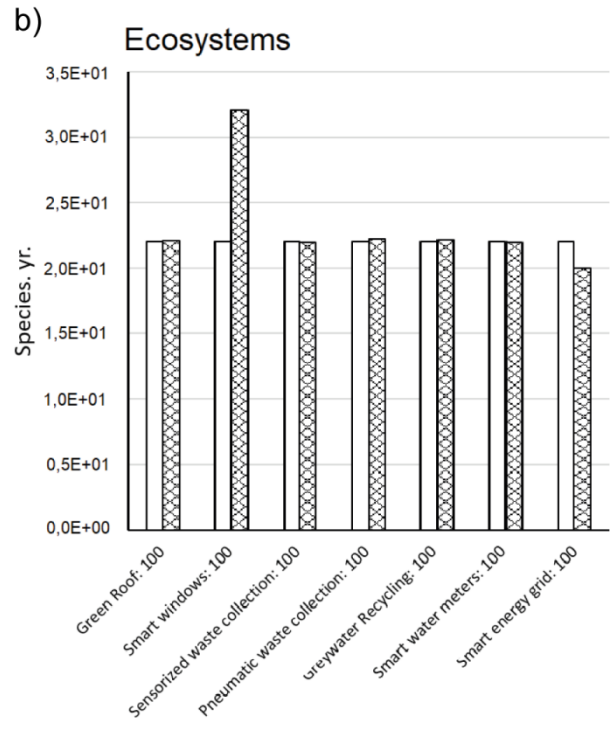
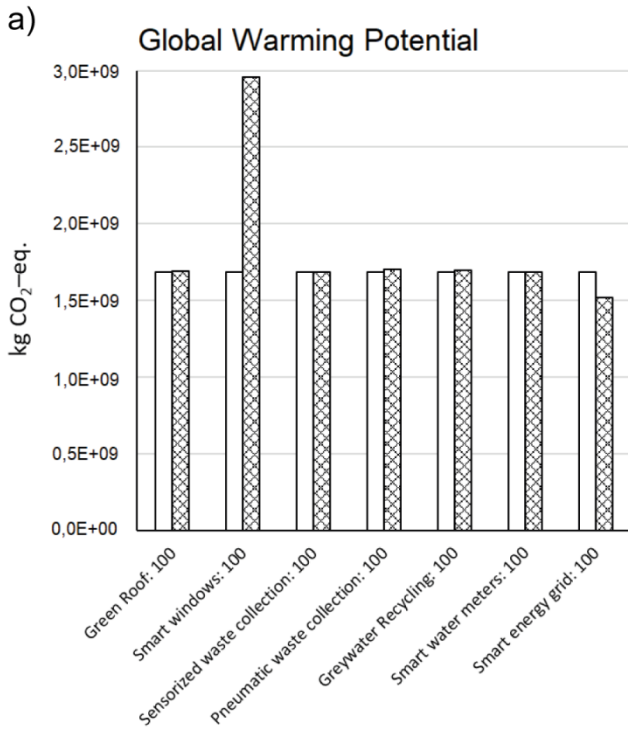


621

622

623

Figure 7:



Copenhagen
  Smart Copenhagen

624

625

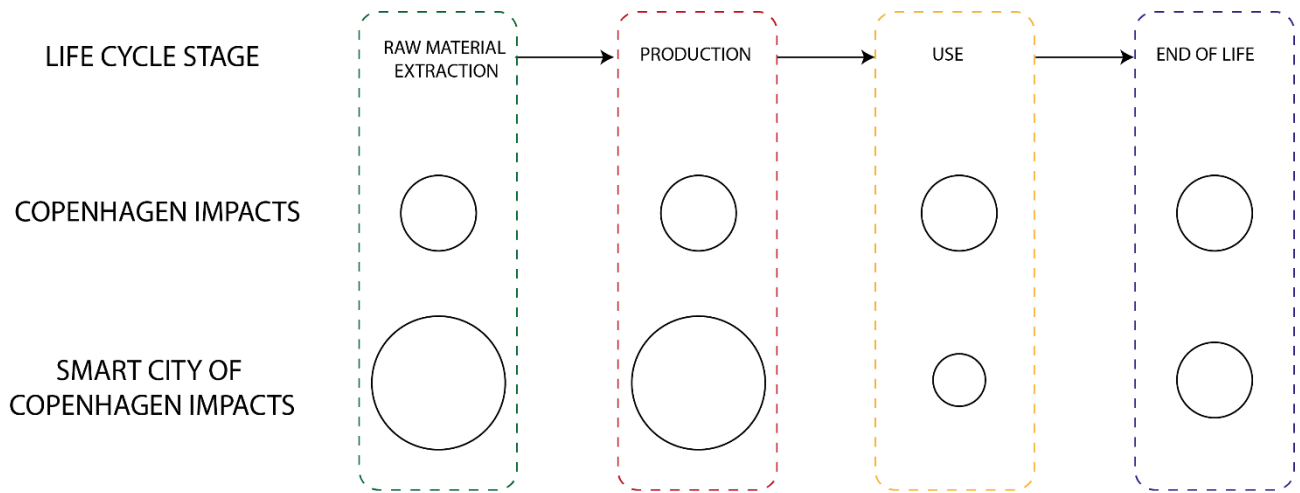
626

627

628

629

630 Figure 8:



631