

2011 International Conference on Green Buildings and Sustainable Cities

Towards a more holistic approach to reducing the energy demand of dwellings

André Stephan^{a,b,c*}, Robert H. Crawford^c, Kristel de Myttenaere^b

^a*Aspirant du F.R.S-FNRS - Belgian National Fund for Scientific Research Fellow*

^b*Building, Architecture and Town planning, Université Libre de Bruxelles, 50 Av.F.-D. Roosevelt, Brussels 1050, Belgium*

^c*Faculty of Architecture, Building and Planning, The University of Melbourne, Victoria 3010, Australia*

Abstract

Buildings consume around 40% of the final energy in most countries but are also responsible for a large part of the energy use in the industrial and transport sectors. Today, most policies and market trends focus solely on the space heating and cooling demands often neglecting to consider indirect energy requirements such as the embodied energy of buildings or the transport energy of their users. This paper assesses different building scenarios located in two urban contexts by integrating the operational energy demand as well as the embodied energy of the dwellings and the transport energy consumption of the users. Results show that space heating represents at most 23% of the total life cycle energy demand over 50 years and 47% if the rest of operational energies, i.e. domestic hot water and appliances, is considered. Transport consumes 34-51 % of the total life cycle energy consumption while the embodied energy of buildings was found to be of the same order of magnitude as their operational energy. Current energy assessment of buildings therefore often only analyses a small fraction of the total life cycle energy use. We should widen its scope to account for so-called indirect energy consumption. This paper shows that a more holistic approach to the assessment of the energy demand associated with buildings is necessary if significant improvements in their energy efficiency are to be achieved.

© 2011 Published by Elsevier Ltd. Selection and/or peer-review under responsibility of APAAS

Keywords: Life cycle energy assessment; buildings; users; transport energy; embodied energy; operational energy; cities; dwellings.

1. Introduction

Buildings represent around 40% of the final energy use in most countries [1], which makes them the

* Corresponding author. Tel.: +32-2-650-66-04; fax: +32-2-650-65-84

E-mail addresses: andre.stephan@ulb.ac.be.

most energy intensive single sector [2]. This has driven governments and building designers to improve the energy efficiency of buildings, especially regarding their heating and cooling demands. Policies such as the Energy Performance of Buildings Directive [3] in Europe and the National Strategy on Energy Efficiency in Australia [4], have enforced the practice into building codes. Low-energy buildings act as best practice regarding efficiency. Among these, the passive house dramatically reduces the heating demand of buildings [5] but often for a high investment cost [6] both in terms of finance and energy.

The current trend focuses solely on operating energy and improving the efficiency of buildings in this regard. While this is a praiseworthy approach, addressing one stage of the life cycle of buildings could result in an increase in others [7]. It is also important to address the energy use of buildings and their users at different scales of the built environment and across the lifespan of the building [8]. The user, scale, and time dimensions hence tackled correspond to a more holistic approach to sustainability as defined by de Myttenaere [9].

The aim of this paper was hence to reveal the importance of integrating the embodied energy of buildings and transport energy of their users. An illustration of this holistic approach is given through a pilot application on various new residential building scenarios in Belgium.

2. Background

The operating energy which is tackled today represents one of the life cycle stages of a building and focuses on the local scale of constructions. The other life cycle stages and scales of the built environment are often not addressed. This section describes the embodied and transport energies of buildings and their users.

2.1. *The embodied energy of buildings*

Materials undergo energy consuming industrial processing before being integrated into a building. This sum of energy inputs required along the production chain of building materials and for their construction is called embodied energy. Different methods have been developed to assess the embodied energy of building materials. A process analysis uses the known production processes and quantifies the energy input but often ignores many smaller and higher order unknown processes. While this method produces accurate figures for the known processes it has been shown that the truncation of the product system boundary can omit up to 87% of the embodied energy [10]. An input-output analysis uses data at a whole sector scale to determine the energy flows [11]. However, this top-down method does not produce very accurate results regarding all products since specific processes are not tackled. Hybrid approaches combine both process analysis and input-output analysis and are often systemically complete. Treloar [12] developed the input-output-based hybrid analysis which is currently the most comprehensive embodied energy assessment technique. This approach relies on disaggregated input-output tables in which the more reliable process analysis figures replace the process within the input-output model, where available. This approach typically results in higher numbers regarding embodied energy compared to the typical process approach due to the more comprehensive system boundary.

Some studies have integrated the embodied energy of buildings and compared it to the operating energy [13-16]. Typically, these studies show that over the lifespan of the building (typically 50 or 100 years), the operating energy share is still dominant (80-90%) [17]. However, these findings are questionable since they are based on the systemically incomplete process analysis for calculating embodied energy. This leads to a significant underestimation of the energy embodied in the buildings. Other research, using the input-output-based hybrid analysis show that the embodied energy is as important as the operating energy over the lifespan of the building [7]. These observations highlight the

importance of embodied energy and imply that today's energy assessment of buildings which most often focuses solely on operating energy could be missing as much as half of a building's life cycle energy consumption.

2.2. The transport energy of building users

The share of transport energy, including all transport means for goods and people, has steadily increased in the last 20 years in most OECD countries [18, 19]. However, road passenger transport has dominated the trend [19] accounting for nearly 50% of total transport energy.

In order to analyze this energy, studies linking urban form and transport energy have emerged. Many of these find great correlation between land-use parameters and transport energy [20-23]. Indeed, other factors such as population density, urban mix, urban intensity, public transport availability and others linked to the built environment have been correlated to transport energy. Since urban form is generated by the arrangement of buildings, transport energy is linked to buildings, on a large scale. At the same time, this study aims at assessing the energy consumption of buildings but also their users. Since building users consume large amounts of energy for their mobility, it is crucial that transport energy demand is included [24]. Ignoring the transport energy in any assessment of building energy demand could lead to situations in which people move to a very efficient house in the suburbs, inducing a surge in their transport energy. The amount of building-related operational energy saved could be outweighed by the increased energy consumption linked to transport. This is already seen as a key problem in many cities around the world [25].

The transport energy of users is not limited to the direct use of fuels or other energy medians to generate a certain mobility. In order to tackle the full energy impact of the users' mobility, the so-called indirect energy, i.e. the embodied energy of used vehicles and infrastructure, should also be accounted for [26].

2.3. Research questions

The previous observations lead us to the following research questions:

- Does operating energy, notably space heating and cooling, represent the most significant component of the total life cycle energy consumption of buildings and their users?
- What proportion of the total life cycle energy associate with buildings do the embodied and transport energies represent?

3. Research Approach

This section describes the method used to quantify the total life cycle energy associated with different scenarios for dwellings in a suburban and city context. Since the aim of this paper is to reveal the importance of combining the different energies and addressing the problem using a more holistic approach rather than conducting a detailed energy analysis, average values based on statistics and relevant literature are used.

3.1. Case study

Two dwellings, one in a suburban area and the second in the city are studied. Each household is composed of two people based on [27, 28]. For each dwelling, three levels of energy performance and linked embodied energy are tested:

- an extremely insulated and airtight passive house equipped with mechanical ventilation and a heat recovery system;
- a low-energy house with reinforced insulation and low space heating energy demand but with standard heat delivery systems;
- a standard new construction built according to the minimal energy efficiency requirements based on the Energy Performance of Buildings Directive [3].

The first household is located in a new typical Walloon detached house with 130 m² of floor area [27]. The house is assumed to be located in a suburban area south-west of Brussels. The second dwelling consists of a 90 m² apartment, typical of new constructions in the city of Brussels [28]. The lifespan of the dwelling is assumed to be 50 years. The suburban house is supported by a reinforced concrete (RC) structure and has a brick fa ade. The city apartment is part of typical 4 stories new RC terraced four stories houses with colored coating fa ades.

3.2. Household operating energy

In this study, the operating energy is separated into three parts: space heating (SH), domestic hot water (DHW) and appliances and others (AO). Cooling is not considered as residential buildings equipped with cooling systems are extremely rare in Belgium. The DHW and AO demands are assumed to be independent of the building construction type and are hence assumed to be the same for the three types assessed for each location: 12.96 and 12.53 GJ/annum for the DHW and 25.2 and 17.1 GJ/annum for the AO for the suburban and city-based houses respectively, based on regional statistics [27, 28]. Regarding the SH demand, three scenarios are tested: passive house, low-energy house and average new construction. The SH demand is fixed at 54 MJ/m².a (15 kWh/m².a) for the passive house [5], 180 MJ/m².a (50 kWh/m².a) for the low-energy house [29] and 306 MJ/m².a (85 kWh/m².a) for an average new construction [27, 30]. These figures are then multiplied by the floor area to obtain the final SH energy demand. DHW and SH are operated with natural gas while AO are operated with electricity (mainly nuclear and gas fueled power plants in Belgium). Only the passive house SH demand is considered as electrical since heat is delivered through preheating of the intake air [5, 31]. The primary energy conversion factors are taken as 1 for natural gas and 2.5 for electricity based on [3]. These numbers are then multiplied by the lifespan of the building (50 years) to obtain life cycle operational energy demand.

The life cycle operational energy demand is calculated according to the following formula:

$$LCOE = (SH + DHW + AO) \times L$$

Where *LCOE* is the life cycle operational energy demand in GJ; *SH* is the annual space heating demand in GJ; *DHW* is the annual domestic hot water demand in GJ; *AO* is the annual appliances and other energy demand in GJ; and *L* is the assumed lifespan of the building i.e. 50 years.

3.3. Building embodied energy

The embodied energy of the studied buildings is based on findings from previous works [15, 17, 32], for cases based on the EcoInvent database which is relevant for western Europe. These studies attribute 2.8 GJ/m² for an average new house, 3 GJ/m² for a low-energy house and 3.6 GJ/m² for a passive house, of initial embodied energy. However, these all rely on process analysis which provides conservative numbers due to the limited scope of the embodied energy system boundary. In order to correct this deficiency a multiplication factor based on the ratio between process analysis and the more comprehensive input-output-based hybrid analysis figures is used. In a case study done by Crawford [7]

on a typical new residential construction in Melbourne, Australia, this factor equals 3.78. The process-based figures are hence multiplied by this factor to provide a more comprehensive value for the embodied energy of the assessed dwellings. The specific embodied energy figures obtained are then multiplied by the floor area of each house.

In addition to the initial embodied energy, a recurrent embodied energy, accounting for maintenance and replacement of materials over the life of the house, is assumed to be 0.5% of the initial embodied energy per annum and hence accounts for 25% of the initial embodied energy. Also, Crowther [33] has found that the energy associated with the demolition and disposal of buildings accounts for less than 1% of the initial embodied energy and therefore it has been excluded in this study. The life cycle embodied energy is calculated as follows:

$$LCEE = EE \times A \times C + (EE \times A \times C \times D \times L)$$

Where *LCEE* is the life cycle embodied energy in GJ; *EE* is the specific process based embodied energy factor in GJ/m²; *A* is the floor area of the house in m²; *C* is a literature-based coefficient to convert process-based embodied energy figures to input-output-based hybrid analysis figures i.e. 3.78; *D* is the annual recurring embodied energy coefficient i.e. 0.005; *L* is the lifespan of the dwelling i.e. 50 years

3.4. Building users transport energy

Only car related transport is considered in this paper. It is composed of direct and indirect requirements. The direct transport energy is associated with fuel consumption while vehicles and road embodied energies constitute the indirect component.

The figures used are based on [34]. The suburban householders are assumed to own two cars which are operated 280 km and 110 km per week respectively and have fuel efficiencies of 8l/100 km or 2.7 MJ/km and 6l/100 km or 2 MJ/km respectively. The first car is operated 40 weeks per year while the second is run all year. The resulting direct annual primary energy of 41 680 MJ is 10% lower than the regional household average of Wallonia [34]. The Brussels scenario uses a single car covering 140 km per week with a fuel efficiency of 6l/100 km or 2 MJ/km according to [34]. According to these assumptions, the annual car transport energy of 12 480 MJ is 6% lower than for the average household in Brussels [34].

The embodied energy of all cars is fixed at 270 GJ/unit based on [24] and a replacement rate of 10 years is assumed. In addition to that, the embodied energy share of the last road section (500 m) serving the neighborhood is considered. The suburban setup is composed of a typical cul-de-sac layout with 40 houses (80% of plots are assumed to be built). The Brussels city location is on the other hand, on a road providing access for 140 houses (all plots are built). These numbers are based on the average size of the plot in suburban and city land studied by Halleux [35]. The life cycle embodied energy coefficient per linear length of road (5 m width) is assumed to be 27 GJ/m based on [36]. The life cycle transport energy is hence calculated according to the equation hereunder.

$$LCTE = \sum_{i=1}^I \left[DIST_i \times F_i \times W_i + EEC_i \times \frac{L}{LC_i} \right] + R \times \frac{EER}{H}$$

Where *LCTE* is the life cycle transport energy in GJ; *I* is the total number of cars owned by the household; *i* is a car of the household; *DIST* is the average weekly distance traveled in km; *F* is the fuel efficiency of the car in GJ/km; *W* is the number of weeks per year this car is operated; *EEC* is the embodied energy of the car in GJ; *L* is the lifespan of the building i.e. 50 years; *LC* is the lifespan of the car i.e. 10 years; *R* is the road length i.e. 500 m; *EER* is the embodied energy per linear meter of road in GJ/m; *H* is the number of houses served by the road.

3.5. Total life cycle energy demand of a building and its users

The calculation of the life cycle energy demand is given by the formula below:

$$LCE = LCOE + LCEE + LCTE$$

Where *LCE* is the total life cycle energy demand of the building and its users in GJ; *LCOE* is the life cycle operational energy demand of the household in GJ; *LCEE* is the life cycle embodied energy of the building in GJ and *LCTE* is the life cycle transport energy demand of building users in GJ

4. Results and discussion

This section outlines the results of the study and the related discussions.

Table 1: Life cycle space heating (LCSH), operational (LCOE), embodied (LCEE) and transport (LCTE) energies of each scenario and their share of the total life cycle energy demand (LCE). Note figures may not add up due to rounding

Energy type	Suburban			Urban		
	Passive house	Low energy	Normal	Passive house	Low-energy	Normal
LCSH (GJ)	878 (9%)	1 170 (12%)	1 989 (19%)	608 (11%)	810 (14%)	1 377 (23%)
LCOE (GJ)	2 786 (28%)	3 078 (30%)	3 897 (36%)	2 089 (37%)	2 292 (40%)	2 859 (47%)
LCEE (GJ)	2 211 (22%)	1 904 (19%)	1 720 (16%)	1 531 (27%)	1 318 (23%)	1 191 (19%)
LCTE (GJ)	5 122 (51%)	5 122 (51%)	5 122 (48%)	2 070 (36%)	2 070 (36%)	2 070 (34%)
LCE (GJ)	10 118 (100%)	10 104 (100%)	10 738 (100%)	5 690 (100%)	5 680 (100%)	6 120 (100%)

The findings clearly show that in all cases, the operational energy and specifically the space heating demand over 50 years represent less than half of the total life cycle energy consumption. Table 1 shows that the operational energy represents at most 47% of the total life cycle energy. This figure drops to 23% for space heating. The indirect energies associated with the building and its users, which are often not considered at the moment, therefore represent the highest share of the total life cycle energy.

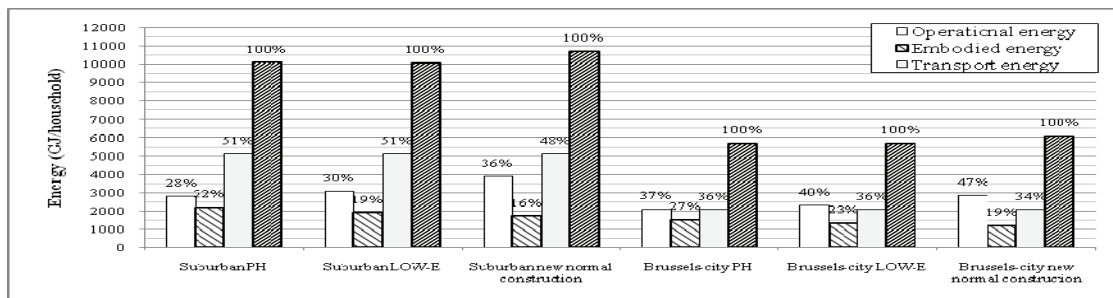


Fig. 1. Total life cycle energy breakdown for each scenario

Fig.1 shows the different contributions of each type of energy for the life cycle energy demand for the different house scenarios. It can be seen that in all cases, the transport energy represents the highest share of the life cycle energy (48-51%) with 5 122 GJ for the suburban case. For the city houses the transport energy represents 34% to 36% of the life cycle energy demand with 2 070 GJ, second after the

operational energy demand. The indirect transport energy, i.e. the embodied energy of the cars and that of the road near the house, accounted for 56% and 68% of the life cycle transport energy for suburban and city scenarios respectively. Public transport has not been considered in this study and may nuance the findings.

The differences in operational energy between each location are associated with space heating since the domestic hot water demand and appliances and others were considered the same for all building types in the same location. The figures for Brussels city are lower than the suburban scenario due to a smaller floor area and a lower average electricity consumption per household.

The embodied energy is of the same order of magnitude as the operational energy in absolute terms for the passive and low-energy scenario. On average, the embodied energy represented 77%, 60% and 43% of the life cycle operational energy for the passive house, low-energy house and normal construction respectively. These figures are higher than what can usually be found in the literature but are comparable to other input-output-based hybrid analysis studies [7].

The total life cycle energy demand of city dwellings has been found to be significantly lower than that of suburban houses even when comparing an average new urban apartment to a suburban passive house. This difference is notably due to the lower transport energy and the smaller size of urban apartments. In fact, the life cycle energy demand of a new normal construction in the city (6 120 GJ) is 39.5% lower than that of a passive house in the suburb while the specific space heating final energy demand of the latter is 82% lower. The difference in life cycle energy is insignificant between the passive and low-energy scenarios for a given location. This is partly due to the assumption that space heating in passive houses is provided through electrical means which has a high primary energy impact. This observation is in accordance with results from [37]. At the same time, the recurring embodied energy was assumed to be the same for all constructions while in reality, passive houses often use high quality certified materials which are more durable and require less maintenance. Consequently, the recurring embodied energy of passive houses is likely to be smaller than what has been assumed here.

5. Conclusion

The total life cycle energy of various residential buildings has been assessed in this paper which gives tendencies rather than a detailed energy analysis. It is clear that the space heating energy, which is the sole focus of current policies and market trends represents only a small proportion of the life cycle energy consumption of a household. It represents at most 23% of the life cycle energy demand and even when the remaining operational energies (domestic hot water, appliances, etc.) are integrated, this number rises to 47%. The embodied energy of buildings along with the transport energy of their users, represent, together, the largest share of the life cycle energy. Since these are often not considered at the moment, subsidies promoting the energy performance of buildings may be directed towards the wrong target. For instance, people living in subsidized low-energy buildings in the suburbs consume more energy overall than their urban counterparts living in sometimes less efficient dwellings. Only by integrating so-called indirect energy consumptions, can the energy assessment of buildings and their users be conducted realistically and hence the energy consumption reduced. A framework that systematically integrates the embodied, operational and transport energy demands and tackles the uncertainty of the assessment techniques is lacking today.

Acknowledgements

This research is funded by the Belgian National Fund for Scientific Research (F.R.S. - FNRS).

References

- [1] International Energy Agency. *Buildings*; 2011
[cited 2011 February 27th]; Available from: <http://www.iea.org/subjectqueries/buildings.asp>.
- [2] International Energy Agency. *Key World Energy Statistics 2009*. Paris: IEA;2009.
- [3] European Parliament and the Council of the European Union. Directive 2002/91/ Ec of the European Parliament and the of the Council of 16 December 2002 on the Energy Performance of Buildings. *Official Journal of the European Communities* 2002;Brussels, p. 7.
- [4] Australian Government: Department of Climate Change and Energy Efficiency. *Buildings*. 2011 22/02/2011 [cited 2011 May 11th]; Available from: <http://www.climatechange.gov.au/what-you-need-to-know/buildings.aspx>.
- [5] Feist W. *Definition of Passive Houses*. Passive Houses; 2006.
- [6] Verbeeck G. Life Cycle Optimization of Extremely Low Energy Dwellings. *Journal of Building Physics* 2007; **31(2)**: 143-77.
- [7] Crawford R. *Life Cycle Assessment in the Built Environment 2011*. London,New York: Spon Press;2011.
- [8] Bokalders, V. and M. Block, The Whole Building Handbook. How to Design Healthy, Efficient and Sustainable Buildings. 2010, London: Earthscan.
- [9] de Myttenaere K, Vers Une *Architecture Soutenable*. Universit  Catholique de Louvain: Louvain-La-Neuve;2006.
- [10] Crawford RH. Validation of a Hybrid Life-Cycle Inventory Analysis Method. *Journal of Environmental Management* 2008; **88(3)**:496-506.
- [11] Suh S, M Lenzen, GJ Treloar, H Hondo, A. Horvath, G. Huppes, et al. System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches. *Environmental Science and technology* 2004; **38(3)**: 657-64.
- [12] Treloar, G.J., Extracting Embodied Energy Paths from Input-Output Tables: Towards an Input-Output-Based Hybrid Energy Analysis Method. *Economic Systems Research* 1997; **9(4)**: 375-91.
- [13] Scheuer, C., G.A. Keoleian, and P. Reppe, Life Cycle Energy and Environmental Performance of a New University Building: Modeling Challenges and Design Implications. *Energy and Buildings* 2003;**35(10)**: 1049-64.
- [14] Cole, R.J. and P.C. Kernan, Life-Cycle Energy Use in Office Buildings. *Building and Environment* 1996;**31(4)**:307-17.
- [15] Sartori, I. and A.G. Hestnes, Energy Use in the Life Cycle of Conventional and Low-Energy Buildings: A Review Article. *Energy and Buildings* 2007; **39**: 249-57.
- [16] Newton P, S Tucker, and M Ambrose. Housing Form, Energy Use and Greenhouse Gas Emissions. In M Jenks, K Williams, and E. Burton, editors. *Achieving Sustainable Urban Form*, E & FN Spon: London ; New York; 2000,p. xii, 388 p.
- [17] Ramesh, T., R. Prakash, and K.K. Shukla. Life Cycle Energy Analysis of Buildings: An Overview. *Energy and Buildings*, 2010; **42**: 1592-600.
- [18] Perez-Lombard, L., J. Ortiz, and C. Pout, A Review on Buildings Energy Consumption Information. *Energy and Buildings* 2008; **40(3)**: p. 394-8.
- [19] International Energy Agency. *Transport, Energy and Co B2 S : Moving toward Sustainability*. Paris: International Energy Agency; 2009,p. 414.
- [20] Newman, P. and J. Kenworthy. Sustainable Urban Form: The Big Picture. In M Jenks, K Williams, and E. Burton, editors. *Achieving Sustainable Urban Form*, E & FN Spon: London ; New York; 2000,p. xii, 388 p..
- [21] Newton P. Urban Form and Environmental Performance. In M Jenks, K Williams, and E. Burton, editors. *Achieving Sustainable Urban Form*, E & FN Spon: London ; New York; 2000,p. xii, 388 p.
- [22] Stead, D., J. Williams, and H. Titheridge. Land Use, Transport and People: Identifying the Connections.In M Jenks, K Williams, and E. Burton, editors. *Achieving Sustainable Urban Form*, E & FN Spon: London ; New York; 2000,p. xii, 388 p.
- [23] Rickwood, P., G. Glazebrook, and G. Searle, Urban Structure and Energy-a Review. *Urban Policy and Research* 2008; **26(1)**: p. 57-81.
- [24] Treloar, G.J., R. Fay, P.E.D. Love, and U. Iyer-Raniga, Analysing the Life-Cycle Energy of an Australian Residential Building and Its Householders. *Building Research & Information* 2000; **28(3)**: p. 184-95.
- [25] Fuller, R.J. and R.H. Crawford, Impact of Past and Future Residential Housing Development Patterns on Energy

Demand and Related Emissions. *Journal of Housing and the Built Environment* 2011; **26**: 165-83.

[26] Lenzen, M., Total Requirements of Energy and Greenhouse Gases for Australian Transport. *Transportation Research Part D-Transport and Environment* 1999; **4**(4): 265-90.

[27] ICEDD. Bilan Energ tique De La Wallonie 2008. *Secteur Domestique Et Equivalents*, 2010. Service public de la Wallonie. p. 132.

[28] Institut Bruxellois pour la Gestion de l'Environnement, Bilan  nerg tique De La R gion De Bruxelles-Capitale 2008, 2010: Brussels.

[29] Thullner, K., Low-Energy Buildings in Europe - Standards, Criteria and Consequences. A Study of Nine European Countries, in *Institutionen f r bygg- och milj teknologi 2010*, Lunds Universiteit: Lund.

[30] Institut Bruxellois pour la Gestion de l'Environnement, Bilan  nerg tique De La R gion Bruxelles-Capitale 2008, 2010: Brussels. p. 215.

[31] Hastings, R., M. Wall, International Energy Agency. Solar Heating and Cooling Programme., and IEA Energy Conservation in Buildings & Community Systems Programme. *Sustainable Solar Housing*, London ; Sterling, VA: Earthscan; 2007.

[32] Gustavsson L. and A Joelsson. Life Cycle Primary Energy Analysis of Residential Buildings. *Energy and Buildings* 2010; **42**(2): 210-20.

[33] Crowther P. Design for Disassembly to Recover Embodied Energy. In *Passive and Low-Energy Architecture* Melbourne-Brisbane-Cairns; 1999.

[34] Institut National des Statistiques. *Transport Routier*. 2010 2009 [cited 2010 October 10]; Available from: http://economie.fgov.be/fr/statistiques/chiffres/circulation_et_transport/transport/routier/.

[35] Halleux, J.-M., Les Co ts De La D surbanisation En Termes D' quipements Et De Services Collectifs, 2003, Universit  de Li ge: Li ge.

[36] Treloar, G.J., P.E.D. Love, and R.H. Crawford, Hybrid Life-Cycle Inventory for Road Construction and Use. *Journal of Construction Engineering and Management* 2004; **130**(1): 43-9.

[37] Dodoo, A., L. Gustavsson, and R. Sathre, Building Energy-Efficiency Standards in a Life Cycle Primary Energy Perspective. *Energy and Buildings* 2011; **43**: 1589-97.