FROM PASSIVE HOUSE TO ZERO EMISSION BUILDING FROM AN EMISSION ACCOUNTING PERSPECTIVE

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Abstract

Norway aims at the establishment of the concept of Zero Emission Buildings (ZEB). The concept related to emission equivalents reaches out beyond the consideration of energy accounted in kWh. Furthermore it is intended to broaden the perspective and include embodied energy in building materials in the emission balance. Moving away from the annual energy budget and including the emissions of the entire building lifetime during construction, operation, and disposal is another key aspect of ZEB. This can be summarised in an emission inventory of operation and building components and services. In this work four concepts for energy efficient buildings are identified which could provide stepping stones towards a definition of ZEB. These concepts will be applied to a generic model (´shoe box model´) of a detached house. The work aims at testing the method of a comprehensive inventory and to investigate the possibilities as well as the boundary conditions of emission accounting.

Introduction

In the context of striving to reduce global warming in the building sector and to build more environmentally friendly buildings Norway aims at establishing and implementing the concept of “Zero Emission Building” (ZEB). However, the controversy about the definition of an environmentally friendly building or even a ZEB and how this can be achieved is ongoing and many possible paths are discussed.

One approach is a further development of the “net-zero energy building” concept. (Sartori, 2010a, p.180) Then ZEB is achieved if a zero balance between imported energy from off-site and exported energy from on-site energy production is established. Two kinds of ZEB's have been identified depending on the physical boundary conditions - “on-site ZEB” and “off-site ZEB”. In case of an “on-site ZEB” the balance is established by solely considering the physical quantity of energy of import and export. The “off-site ZEB” includes a weighting system of e.g. primary energy factors or CO_2 equivalent emission factors in order to evaluate the impact in terms of the energy source (Sartori, 2011 p.4). The temporal boundary condition to define the balancing period is usually one year referring to the annual energy budget.

Contemporary concepts like the passive house standard to achieve highly energy efficient buildings are often linked to an increased use of building materials due to improvements of the building envelope. As a result of this energy efficient measures the embodied energy in the building materials gains more importance while the proportion of operational energy decreases (Thormark, Sartori and Hestnes, Winter and Hestnes cited in Gustavsson, 2010, p.231). Therefore the embodied energy in the building and building systems needs to be included in the accounting balance. Furthermore the balance needs to be extended to the complete life cycle of the building including the construction, refurbishment, and demolition phases of the building. (Sartori, 2010a, p.186) Embodied energy is then not only accounted cradle-to-gate but cradle-to-cradle.

An alternative conception debated in the Norwegian context questions the nature of achieving energy efficiency only by means of technological solutions and high-performance materials. Instead, it promotes moderate measures and natural strategies. Especially the use of building materials based on renewable raw materials and the changes during the life time as well as the possibilities of an after life ("design for salvageability") as design parameters are strongly regarded. Whereas the first approaches account per square meter floor area this concept suggests to account the CO_2 equivalents per capita. (Nordby, 2010. also Berge, 2009)

However, despite the differences in detail the mentioned paths share similarities. They consider the building as a system of energy flows concerning input (supply), operation (consumption), integration (storage), and output (generation) of energy. The working unit to account for these energy flows are in all cases emission equivalents, acknowledging the different energy carriers and sources of energy. All initiatives aim at the reduction of energy consumption of a building and advocate energy efficiency while using human health, well-being, and comfort as starting points.

Objectives

The aim of this paper is to investigate the emission balance of both operational and the embodied energy in different highly energy efficient buildings concepts which are worth considering toward achieving Zero emission buildings. Furthermore the paper aims to determine critical and sensitive input of data for the inventory and its impact on the assessment.

Based on literature studies of scientific resources and national or international standards energy efficient building concepts were identified. These were applied to a generic "shoebox" model used for the comparative analysis of case studies with one base case as reference. Main body of the work are the emission inventories of the case studies. The spreadsheet-based inventories were conducted for the embodied energy of construction materials and building services over one building's life based on the building material databases "EMPA Ökologische Baustoffliste (Version 2.2e)" and "Ökobilanzdaten im Baubereich, Stand Januar 2011" which are extracts of "Ecoinvent 2.2". The boundary conditions are cradle-to-gate. Different lifetimes for the building components were taken into consideration. The operational energy performance was evaluated using the simulation tool "Simien".

This essay is part of ongoing research work being conducted in the ZEB centre. The emission calculation method is based on a method currently being developed by the supervisor of this essay Aoife Houlihan Wiberg (Houlihan Wiberg, 2011). The shoe box model is part of current concepts and strategies package works within the ZEB centre.

Scope and limitations

The study is limited to one building typology and is based on best-case scenario design for the building and the energy generation and supply system. This generic model might not reflect real conditions with a multitude of constraints e.g. site context disadvantages, legal issues, economical limitations and the availability of products in the local Norwegian market.

The variations of the base case are predefined to the availability of alternatives in the databases. The inventories try to encompass the majority of used materials although not all materials are covered.

The configuration of the building does not change during its lifetime. Replacement of components is included in the inventories but limited to present-day state-of-the-art materials and technologies. Future solutions might circumvent today's issues.

Since a comprehensive material database is not available in Norway, there is of course the paradox that the building is conceived for Norwegian conditions and location according to Norwegian standards while it is ´built´ and ´operated´ in Switzerland since average European emission factors are used for energy carrier and materials.

Method

Description of method

The greenhouse gas emissions in kilogrammes CO_2 equivalents over buildings lifetime due to embodied and operational energy will be accounted for three possible approaches towards achieving a Zero Emission Building. A reference building will be used as starting point. The base case is a passive house with reference materials used in the commonly used Norwegian construction. The first case study aims at zero operational energy disregarding the embodied energy in the materials. The second case study tries to reduce the embodied energy based on conscious material choice, while undertaking no efforts to improve the energy performance. In case study three both measures are combined.

The case studies can be illustrated in a matrix where the concepts in the same row have the same energy performance and the concepts in the same column have the same embodied energy (Fig. 1).

Base case reference operational energy reference embodied energy	**Case study 2** reference operational energy reduced embodied energy
Case study 1 reduced operational energy reference embodied energy	**Case study 3** reduced operational energy reduced embodied energy

Figure 1: Matrix of examined cases

Generic model

To evaluate the operational and the embodied energy the energy performance simulation and the inventory of materials and systems are assessed using a generic model (shoebox model) which is used in research in the ZEB centre. The generic model represents the Norwegian building typology of a “small house”. This shoe box model avoids constraints and allows the possibility of using the entire envelope for interventions.

The model is a double-storey residential building where the thermal zone measures two times 10 x 8 metres in plan with a clear height of spaces of 2.40 m. The total usable area BRA (“bruksareal”) is 160 m^2. A rough architectural design is applied to the generic model to obtain a more fine-grained input for the simulations and a more comprehensive inventory of the building. The design also shows a pitched roof with 30 degrees slope to allow the integration of photovoltaic panels. The resulting space is incorporated in the simulations as cold attic. The total building lifetime is assumed as 60 years.

Inventory

The emissions of building components and building services are assessed by means of a self-developed spreadsheet. In some cases additional adjustment factors are employed to mediate between the generic model which uses interior dimensions and exterior dimensions which are used for the inventory. However, these adjustment factors were verified with the actual design. Windows and doors are excluded from the wall areas.

The calculation method developed at the ZEB centre is based on the the Swiss database “Ecoinvent”. The “Ökologische Baustoffliste (Version 2.2e)” (Althaus, 2011) [“Ecological Building material list (version 2.2e)”] by the Swiss Federal Laboratories for Material Science and Technology “EMPA” as of 11.01.2011 is extracted from “Ecoinvent” and is used as database for the materials and also the emission factors of the operational energy in this work. The database is limited to cradle-to-gate and uses average European or Swiss CO_2 equivalent emission factors for the production-related embodied energy. The total emission quantities of the building over lifetime were broken down to square meter BRA. Therefore the working unit is kg CO_2-equiv./m^2 BRA. The same unit is used for both the energy from operation and the embodied energy where the annual emissions from operation were summed up over 60 years.

The accounting can be expressed in the formula:

$$E_{60a} \ per \ m^2 \ BRA = \frac{x \cdot \rho \cdot a \cdot e_0 \cdot t_B}{t_m \cdot A_{BRA}}$$

where E_{60} is the overall emission over 60 years, x is the calculated quantity as volume, ρ is the density of the material, a is an adjustment factor, e_0 is emission factor for one lifetime of the material cradle-to-gate, t_B is the building's lifetime, t_m is the lifetime of the material or unit, and A_{BRA} is the usable area. In case of emissions per unit or lump packages the expression ($x \cdot \rho$) is replaced by the quantity of the unit.

Few items in the inventories were not covered by the “Ökologische Baustoffliste” and are taken from “Ökobilanzdaten im Baubereich, Stand Januar 2011” [“Ecological balance data in the Building sector, state January 2011”] published by the “Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren” (KBOB) [roughly: “Coordination congregation of public contracting building and property management authorities” (KBOB, 2011). However, both Swiss lists are based on “Ecoinvent 2.2”.

In case of building components all layers are included directly or proportionally according to their assumed ratio (studs and steel connectors in case of wall assemblies, for example). The dimensions of envelope elements reflect the energy performance – e.g. required U-values are modelled in the assemblies. The online tool “u-wert.net” was used to find the appropriate dimensions and assess the functionality of the assembly. The densities of the materials are taken from the inventory database except for very specific cases (e.g. “Leca isoblokk 35”) where manufacturer information was used. However, finishes of surfaces (tiles, wall paper, coatings, varnish, etc.) are not included in the inventory and generate a substantial margin of error.

With the aspiration to provide a comprehensive inventory building services are included. As guideline the cost group 400 of the German standard DIN 276-1 “Kosten im Bauwesen – Teil 1: Hochbau” (“building costs – part 1: ”buildings”) was used which comprises an overall outline of technical systems in buildings. For the installed technical systems, devices for generation, distribution, and supply are considered. In most cases the inventory databases provide only lump packages per unit or square meter floor area. Since the details are not available there might be deviations from the actual case. Scaling factors were used to interpolate between database entries and the design specific values. (Example heat pump of base case: The database provides only a value for a 30 kW heat pump while the value of the design is 7.6 kW. Then the factor 7.6 / 30 = 0.267 was applied to the database value of 5060 kg CO_2-equiv./unit.)

Some elements like doors and windows, for example, (but also insulation) have a shorter lifetime than the whole building structure. Especially building services are often replaced three, four times during the estimated 60 years. Thus the one-time emissions when erected are multiplied with factors according to the expected lifetimes of those components. The lifetimes are taken from the book “ENØK i bygninger” (NTNU, 2007).

Energy performance

The operational energy is obtained by simulation of the case studies in the dynamic simulation software “Simien 5.07” which is tailored for Norwegian conditions and requirements. For location, the standard reference climate located in Oslo Blindern is used. The values of delivered energy are taken directly from the software, while the emission factors are taken from the material database for coherence purposes.

Regarding the CO_2 emission factors of operational energy the database provides two options for the energy supply with electricity from the grid. One is the UCTE electricity mix with 595 g CO_2-equiv. / kWh, the other is the Swiss electricity grid with 149 g CO_2-equiv. / kWh. Both values are used in this work. The first may describe the present state. The second one may be used to describe a future scenario with progressive de-carbonisation of the European electricity grid. The latter value is very similar to an internal ZEB centre value of 137 g CO_2-equiv./ kWh which includes progressive de-carbonisation of the electricity grid for the period 2010 until 2050 (Voss, 2011). However, this future scenario would apply only to the operational energy since the embodied energy of materials is still calculated with the present average European electricity mix.

Base case

Definition

Advantages of choosing the passive house concept are its default focus on reduced energy demand. It anticipates the future trend in energy requirements and can demonstrate the forthcoming situation. Technically many of possible passive energy-saving measures are demanded by the passive house requirements. Nevertheless, “passive house” should still be considered as a concept without prescriptions according to its original definition: “A Passive House is a building, for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air.” (PHI) This allows flexibility in realisation of how to achieve this goal and makes furthermore no requirements on materials.

However, since the study aims at Norwegian conditions the base case is modelled according to the national Norwegian “passivhus” standard NS 3700/2010. The design represents the sufficient minimum to pass the criteria.

Description

The construction type and the materials are chosen in compliance with current practise and are widely derived from the “SINTEF Byggforskserien”. The construction in general is very lightweight of traditional platform-framing with insulation between the studs and joists. The principal insulation material is mineral wool above ground level and extruded polystyrene (XPS) below ground. The foundation are made up of a shallow foundation type named “ringmur” commonly used in Norway. Noticeably, very little concrete has been used namely only in the parts adjacent to ground. Since also all internal wall and ceiling surfaces are made of gypsum boards the internal surfaces are very lightweight. This low heat storage capacities result in higher power requirements for the heating system.

The chosen energy supply system for the base case is uncomplicated. Grid electricity covers the specific demand for lighting, equipment as well as for the fans and pumps of the building services. A ground–water heat pump (7.6 kW peak power) supplies the energy for the heating system, the ventilation heating, and the domestic hot water system. The electricity necessary to run the heat pump is supplied by the grid. Consequently, only electricity and no other energy carrier is delivered to the site.

Results of energy performance calculations

The results of “Simien” show a total heat loss factor of 0.55 W/(K·m^2) which is lower than the required 0.70 W/(K·m^2) but necessary to achieve the required heating demand of 20 kWh/m^2.

pos.		energy demand	specific energy demand
1a	space heating	2758 kWh	17.2 kWh/m²
1b	ventilation heating	411 kWh	2.6 kWh/m²
2	domestic hot water	4765 kWh	29.8 kWh/m²
3a	fans	701 kWh	4.4 kWh/m²
3b	pumps	477 kWh	3.0 kWh/m²
4	lighting	1822 kWh	11.4 kWh/m²
5	equipment	2803 kWh	17.5 kWh/m²
total net energy demand		**13738 kWh**	**85.9 kWh/m²**

Figure 2: base case, energy budget

The energy budget (Fig. 2) shows typical values for energy efficient buildings with optimised performance where only 32 % of the operational energy are building-related to maintain comfort conditions by heating. On the other hand, lighting, equipment, and hot water which depend on the user make up 68 % of the net-energy demand. The net-energy demand for domestic hot water is almost twice as much as the heating demand.
A similar proportion can be observed in case of the delivered energy (Fig. 3)

energy source	delivered energy	specific energy demand
direct electricity	5803 kWh	36.3 kWh/m²
el, heat pump	3574 kWh	22.3 kWh/m²
total delivered energy	**9377 kWh**	**58.6 kWh/m²**

Figure 3: base case, delivered energy

Only a minority of the delivered energy is used for the heat pump which provides energy for heating and hot water. 8.9 kWh/m² can be ascribed to the heating which is 15 % of the total delivered energy.

Results of emission inventory

16 elements, thereof 12 building components and 4 building service system, form the inventory. At first shown only the proportions of embodied energy over lifetime (Fig. 4)

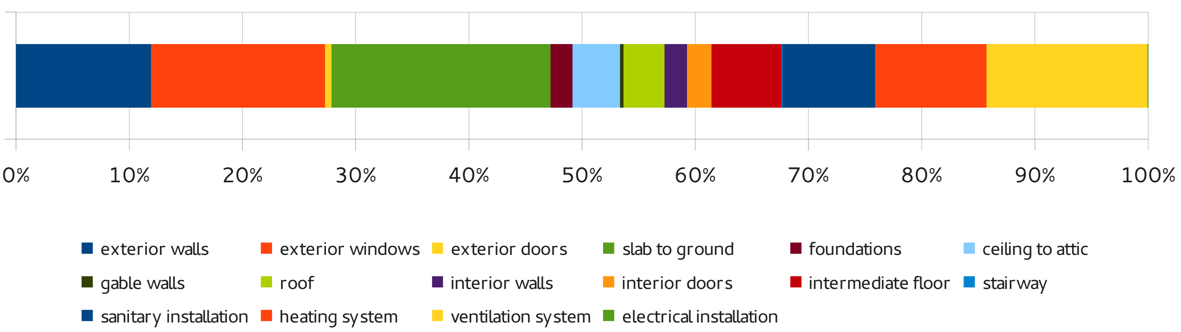

Figure 4: base case, emissions from building components and services

68 % of the embodied energy is related to the building components and 32 % is connected to the technical systems where the ventilation has the biggest share due to its assumed lifetime of 15 years, while the electrical installation share is vanishingly small. The biggest share belongs to the slab to ground which is responsible for 20 per cent of all emissions. Due to

their estimated short lifetime windows with only 22.5 m² area account for 15 % while the 207.6 m² exterior walls contribute 12 % of the total embodied emissions. It is noteworthy that interior structures account for 10 % of the embodied energy. In total, 515 kg CO_2-equiv./m² BRA global warming potential can be ascribed to the embodied energy over the building's lifetime.

Below the specified emissions for the selected building components exterior wall, slab to ground, and the intermediate floor (Fig. 5, 6, 7):

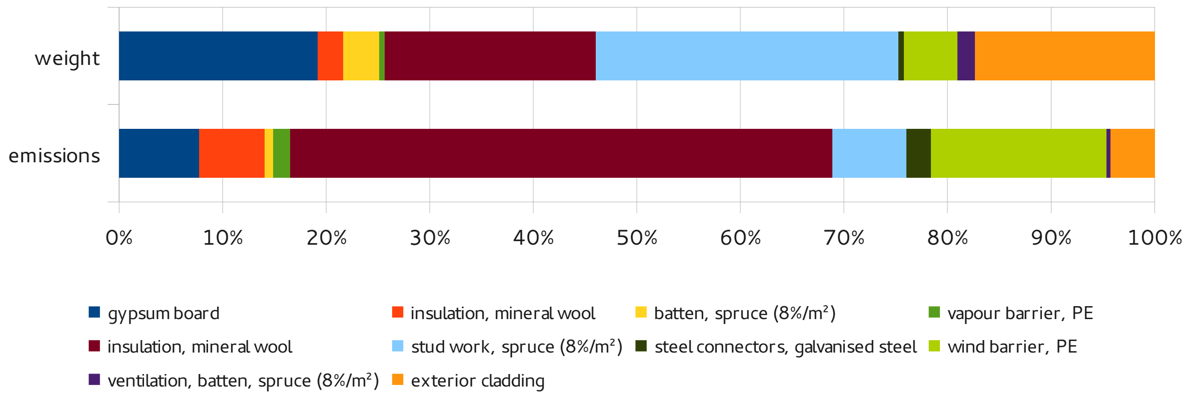

Figure 5: base case, exterior wall

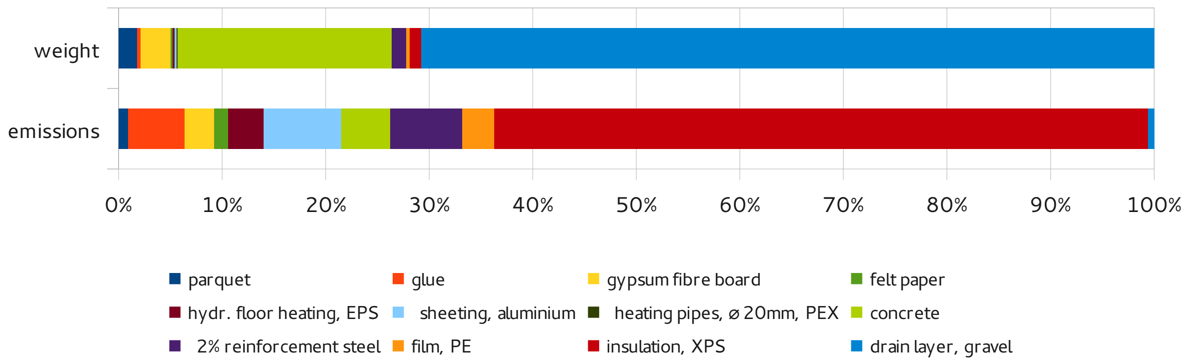

Figure 6: base case, slab to ground

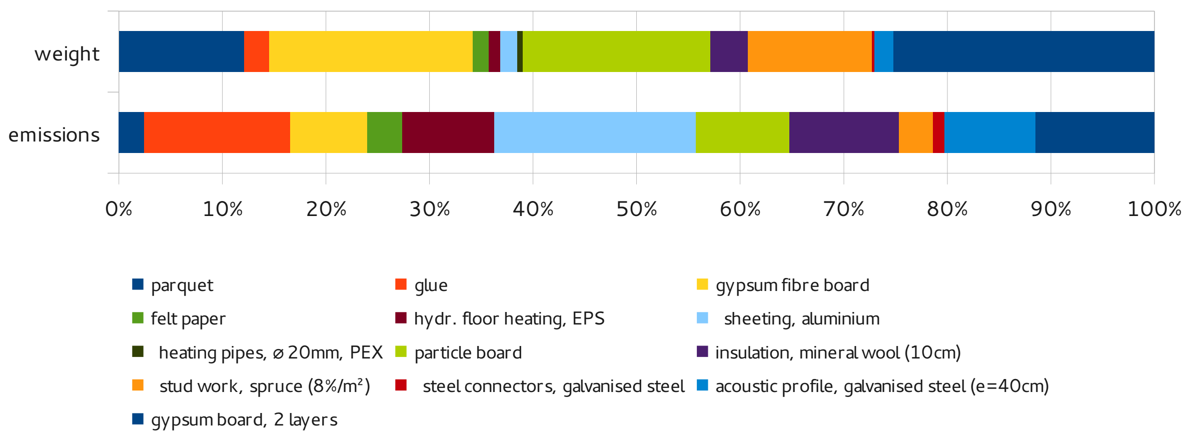

Figure 7: base case, intermediate floor

The results show big differences between the weight and emissions. Especially the difference between weight and emissions for synthetic materials like insulation, plastics on one hand and metal products on the other is big even though this materials are used only in small quantities and thin layers. A dramatic example is the XPS insulation in the slab to ground which accounts for over 60 % of the emissions while it accounts only for 1 % of the weight, yet 51 % of the volume.

When looking at embodied and operational energy combined it is useful to distinguish the two separate cases of UCTE electricity mix and the Swiss electricity mix (Fig. 8)

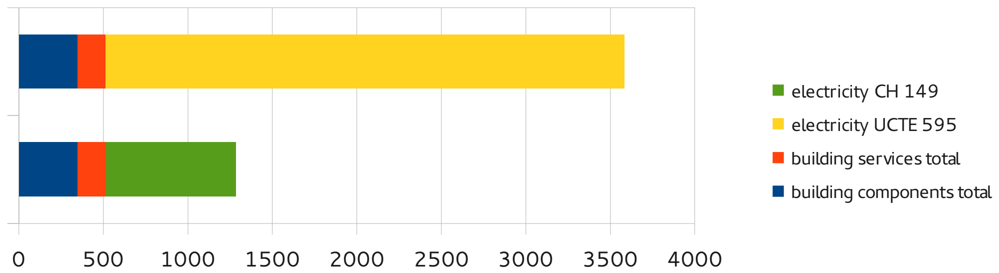

Figure 8: base case, overall emissions over lifetime

In case of the UCTE electricity mix the total emissions over 60 years account for 3585 kg CO_2-equiv./m² where emissions from operational energy contribute 86 %. On the other hand, assuming a cleaner grid as the Swiss electricity grid total emissions are 1284 kg CO_2-equiv./m² where the emissions from embodied energy account for 40 % of the total emissions over the building's lifetime.

Case study 1

Definition

The concept of the "Net Zero Energy Building" ("Net ZEB") describes a building not autonomously depending solely on on-site generation of energy but interacting with the off-site energy infrastructure. The approach is reflected in the usage of the prefix "net" to express the necessity of an balance between energy imported from and exported to the grid. In case of Net ZEB the energy taken from the infrastructure is totally balanced by on-site generation of energy from renewable resources (Sartori, 2010b).

Relevant issues in the balance are the balance boundary (aka the energy uses which are included in the balance), the balancing period, and the weighting metrics. As balancing items and balancing period vary from country to country, in the Norwegian context the energy demand requirements and the annual energy budget according to NS 3031 can be used. To evaluate adequately the balance of import and export a weighting system is necessary to describe the quality of the energy carrier. These credits can be expressed in primary energy or CO_2 equivalent emission factors (Sartori, 2011).

In this case study the import and export happens only by means of electricity. Hence the balance can be simplified and the weighting factors can be assumed as equal. The intended installation of photovoltaic cells is dimensioned to cover the annual electricity demand fully and thus the emissions from operational energy can be considered as zero. Hereby, this case study fully corresponds with the definition of a Zero Emission Building according to the first possible definition in the introduction.

Changes compared to base case

Photovoltaic cells are installed on both the south- and north-facing roof slope with an installed power of 8.5kW$_p$ on either side. As building-integrated photovoltaics they fill out the entire roof area and replace all roofing tiles of the base case. According to an estimation of the annual produced electricity with “PVGIS” approximately 9900 kWh can be yielded over the year. Considering no generation during the winter from mid December to mid March due to snow only 9000 kWh are considered for the calculations. Taking into account the seasonal imbalance 40 per cent of the annual electricity demand have to be sourced from the grid which are then balanced with the overproduction during the summer months. (Fig. 9, 10)

Electricity demand		**Photovoltaics**			**Direct electricity**		
		PV supply	coverage by PV		coverage by grid-el		off-set el
[kWh]		[kWh]	[kWh]		[kWh]		[kWh]
Jan	-920.7	0.0	0.0	0%	921	100%	0.0
Feb	-833.4	0.0	0.0	0%	833	100%	0.0
Mar	-837.3	327.5	327.5	39%	510	61%	0.0
Apr	-699.6	1090.0	699.6	100%	0	0%	390.4
May	-689.6	1614.7	689.6	100%	0	0%	925.1
Jun	-614.6	1756.3	614.6	100%	0	0%	1141.7
Jul	-635.4	1643.4	635.4	100%	0	0%	1008.0
Aug	-635.4	1193.9	635.4	100%	0	0%	558.5
Sep	-664.0	718.7	664.0	100%	0	0%	54.7
Oct	-727.0	407.2	407.2	56%	320	44%	0.0
Nov	-801.9	174.8	174.8	22%	627	78%	0.0
Dec	-895.0	48.3	48.3	5%	847	95%	0.0
total	**-8953.9**	**8974.8**	**4896.4**	**60%**	**4057.4**	**40%**	**4078.4**

Figure 9: case study 1, energy supply

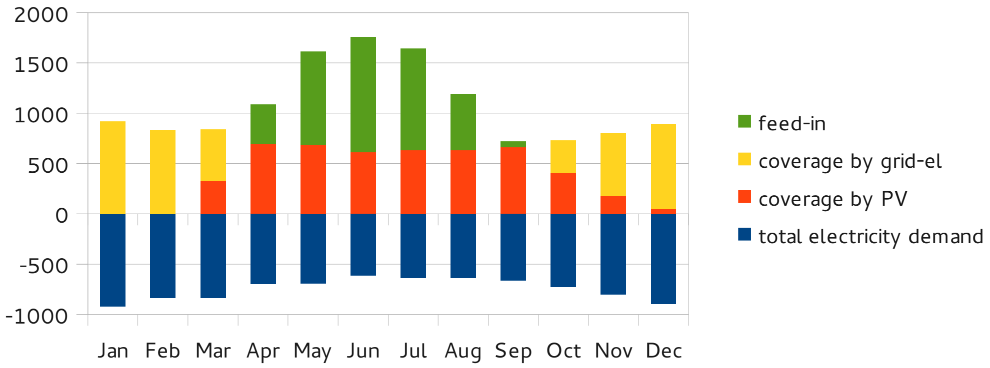

Figure 10: case study 1, annual energy supply balance

In order to achieve a total of delivered electricity of less than 9000 kWh improvements to the building envelope are necessary. Consequently the U-values of walls and ceiling were improved from 0.09 to 0.06 W/(m²·K) and the normalised thermal bridge value reduced. The increased insulation also lead to a reduction of the installed power for heating (7.1 kW). Other measures were not considered as they can not be reflected in the inventory (e.g. improved windows or heat recovery).

Results of energy performance calculations

Calculations show that the heating demand has drastically reduced as a result of the insulation measures (Fig. 11). The domestic hot water has the highest energy demand of all and is more than two times higher than the heating demand. The total net-energy demand is reduced from 86 kWh/(m²·a) in the base case to 80 kWh/(m²·a).

pos.		*energy demand*	*specific energy demand*
1a	space heating	1889 kWh	11.8 kWh/m²
1b	ventilation heating	386 kWh	2.4 kWh/m²
2	domestic hot water	4765 kWh	29.8 kWh/m²
3a	fans	701 kWh	4.4 kWh/m²
3b	pumps	450 kWh	2.8 kWh/m²
4	lighting	1822 kWh	11.4 kWh/m²
5	equipment	2803 kWh	17.5 kWh/m²
total net energy demand		**12816 kWh**	**80.1 kWh/m²**

Figure 11: case study 1, energy budget

The delivered energy is reduced to less than 9000 kWh. Reduction takes place on the heat pump side where now only 11 % (6.4 kWh/m²) delivered energy are necessary for the heating (Fig. 12).

energy source	*delivered energy*	*specific energy demand*
direct electricity	5776 kWh	36.1 kWh/m²
el, heat pump	3171 kWh	19.8 kWh/m²
total delivered energy	**8947 kWh**	**55.9 kWh/m²**

Figure 12: case study 1, delivered energy

Results of emission inventory

The improvements of the envelope and in particular the installation of the photovoltaics are clearly noticeable in the chart of the emission from embodied energy (Fig. 13).

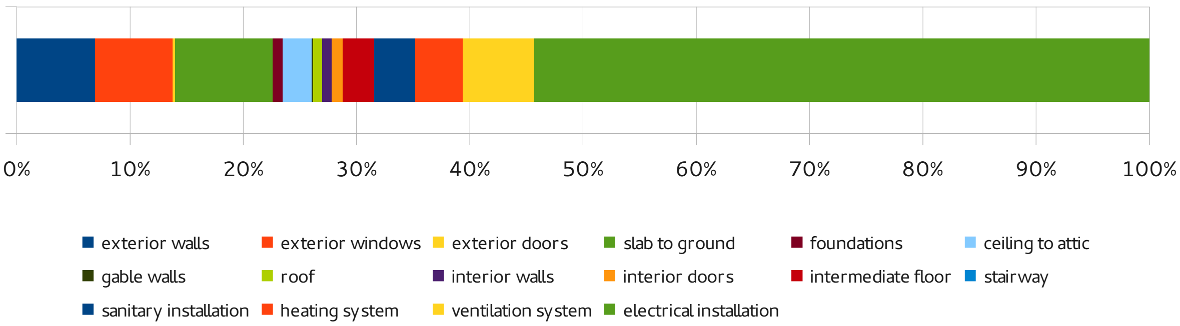

Figure 13: case study 1, emissions from building components and services

The emissions from embodied energy have increased to 225 % of the emissions of the base case. The building components account only for 32 % of the emission whereas the building services account for 68 % mainly due to the photovoltaics which make up 54 % of the emissions from embodied energy.

The increased insulation can be seen in case of the ceiling to the cold attic and the exterior wall where the emission have increased by one third. The mineral wool accounts now for 60 % of the emissions (Fig. 14). The slab to ground and the intermediate floor were not subject to changes.

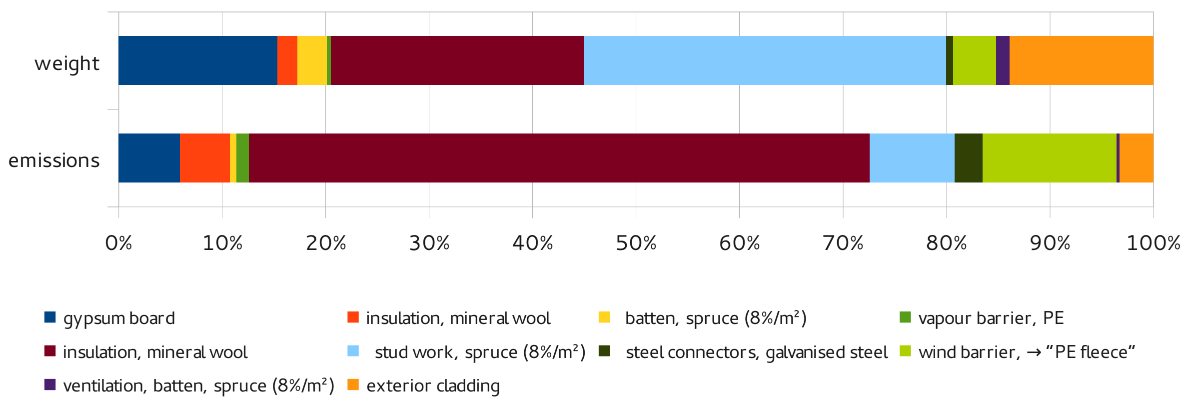

Figure 14: case study 1, exterior wall

Since the emissions from operational energy are assumed zero only the emissions from the materials and building services are accounted over the building's lifetime (Fig. 15).

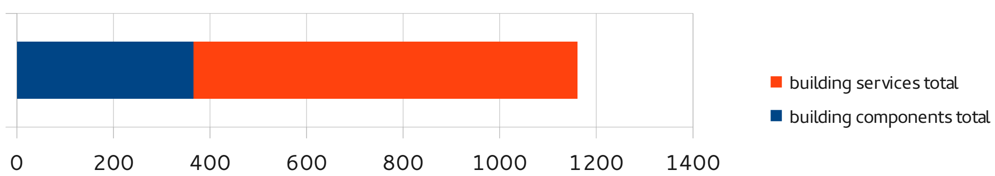

Figure 15: case study 1, overall emissions over lifetime

When comparing the total emissions over lifetime of approximately 1160 kg CO_2-equiv./m^2 BRA to the base case with UCTE electricity mix, the overall emissions are reduced by 67 %. However, assuming the cleaner grid represented by the Swiss electricity mix then the reduction accounts for only 10 %.

Case study 2

Definition

"HAUS der Zukunft" ("Building of tomorrow") is a research and development initiative of the Austrian Federal ministry for transport, innovation and technology. Vision is to increase the efficiency regarding production and operation in order to reduce the emissions over the buildings life cycle to zero. The three columns of the conception are energy efficient buildings e.g. the passive house concept, integration of solar energy supply systems, and the use of ecological materials based on renewable biological raw materials. (HAUS der Zukunft, 2011)

Several projects on latter field were carried out by the "Gruppe Angepaßter Technologien" ("Centre for Appropriate technology", GrAT) at the TU Vienna investigating the fields of application, the possible market penetration of renewable raw materials as well as establishing the internet platform "NAWARO" ("NAchWAchsende ROhstoffe" ("renewable raw materials")) for the building sector. Part of the research was the construction of the demonstration building "S-House" and the development of best practise detail solutions which are available on "NAWARO". (Projektfabrik, 2002. GrAT, 2002)

Part of the strategy is the application of Carbon sequestration in the renewable raw materials, for example the extensive use of wood and wood-based products. These are then taken into account in the carbon emission balance as negative modifiers. Hereby a negative emission balance can be achieved for many materials and entire building components (Fechner, 2002. see also Berge, 2009).

However, this work follows the "Ecoinvent 2.2e" database which does not include modifiers for carbon sequestration in the production related emission. Instead the emissions from disposal have been reduced significantly (Althaus, 2011). Since disposal is not included in this inventory these reductions cannot be assigned to the materials. For the same reason the usage of recycled materials which are a corner stone of the concept can not be depicted. Consequently, a "net-zero embodied energy building" as originally intended for this work cannot be achieved within this framework.

Changes compared to base case

The construction and the layering of the building components was changed following the details proposed by "NAWARO". However, the changes could not be as fundamental due to the limitation of the database. Plastic and synthetic material have been avoided. Mineral wool is substituted with cellulose and wood fibre insulation, for example. Having chosen a diffusion-open construction the plastic vapour barrier is replaced by OSB/3 sheeting. Also the wind barrier of polyethylene fleece has been replaced by wood fibre board. An important change is the usage to heavy-weight construction. Due to cross-laminated timber slabs for the floor and ceiling, concrete screeds as sub floor, and interior surface renderings with 20 mm clay boards the heat storage capacities of the inner surfaces could be changed to “medium-heavy” in “Simien”. Furthermore the linear foundations were replaced by a single load bearing concrete slab resting on foamed glass insulation.

Results of energy performance calculations

The increased heat storage capacity leads to a reduced demand of installed power for the heat pump (5.7 kW instead of 7.6 kW as in the base case). The specific net-energy demand decreases from 86 to 85 kWh/m² (Fig. 16)

pos.		*energy demand*	*specific energy demand*
1a	space heating	2844 kWh	17.8 kWh/m²
1b	ventilation heating	358 kWh	2.2 kWh/m²
2	domestic hot water	4765 kWh	29.8 kWh/m²
3a	fans	701 kWh	4.4 kWh/m²
3b	pumps	310 kWh	1.9 kWh/m²
4	lighting	1822 kWh	11.4 kWh/m²
5	equipment	2803 kWh	17.5 kWh/m²
total net energy demand		**13603 kWh**	**85.0 kWh/m²**

Figure 16: case study 2, energy budget

The delivered energy also decreases slightly (Fig. 17).

energy source	*delivered energy*	*specific energy demand*
direct electricity	5636 kWh	35.2 kWh/m²
el, heat pump	3589 kWh	22.4 kWh/m²
total delivered energy	**9225 kWh**	**57.7 kWh/m²**

Figure 17: case study 2, delivered energy

Results of emission inventory

The changes in the construction show less dramatic deviations from the base case than the first case study in terms of distribution of emissions in the building components (Fig. 18).

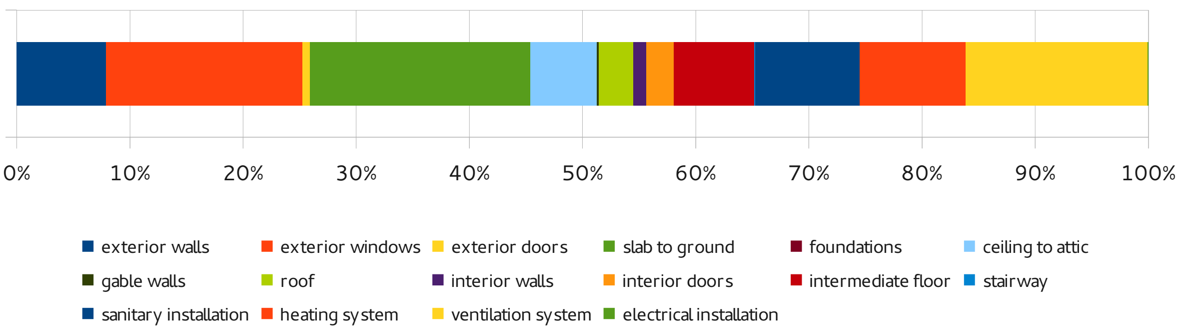

Figure 18: case study 2, emissions from building component and services

The proportion of building services (65 %) to building components (35 %) has slightly changed compared to the base case although the reduction of installed power lead to a reduction for emission related to the heating system by 16 %. In total, approximately 455 kg CO_2-equiv./m²

BRA can be ascribed to the building components which is 88 % of the base case.

The changes in components with a construction (wall, roof) similar to the base case shows significant changes from the substitution of plastics by 35 to 50 % reduction (Fig. 19).

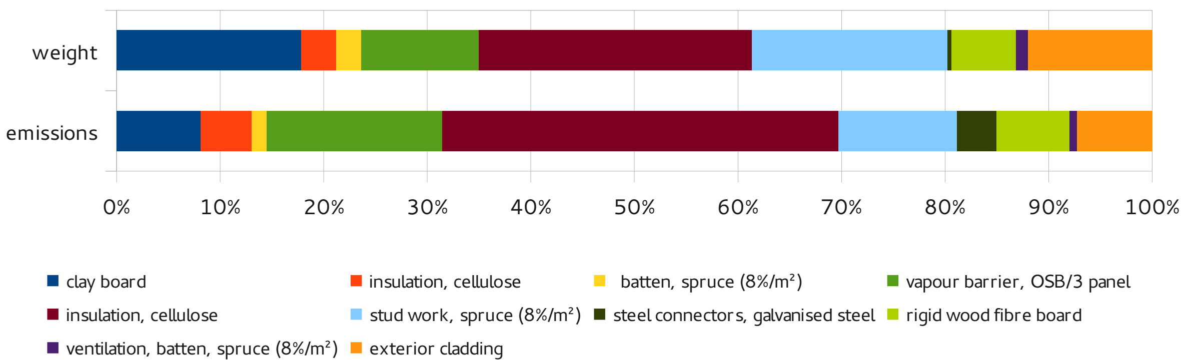

Figure 19: case study 2, exterior wall

In case of the slab to ground the proportion compared to the total emission remains almost constant at 20 % (Fig. 20).

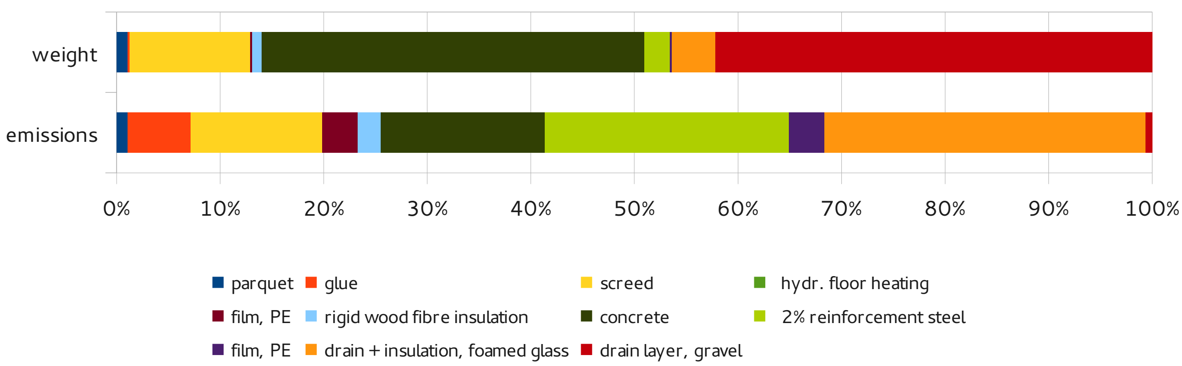

Figure 20: case study 2, slab to ground

Despite the use of a lot more concrete the change of construction leads to a reduction of total emissions of 20 %. The steel used for the reinforcement has a higher impact than the concrete itself.

The use of cross-laminated timber and screed in the floor slabs leads to an slight increase of emissions related to embodied energy (Fig. 21).

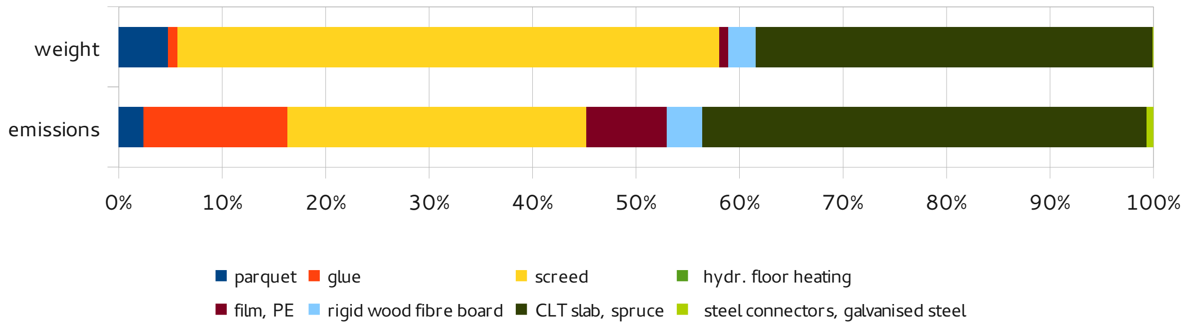

Figure 21: case study 2, intermediate floor

While load bearing construction parts in the base case accounted only for 13 % of the emission the CLT slab accounts for 43 %. In general, the quantity of layers is noticeably reduced and the relationship between weight, volume and emissions is clearer.
Below the results are shown when considering both the emissions related to embodied and the operational energy over 60 years (Fig. 22).

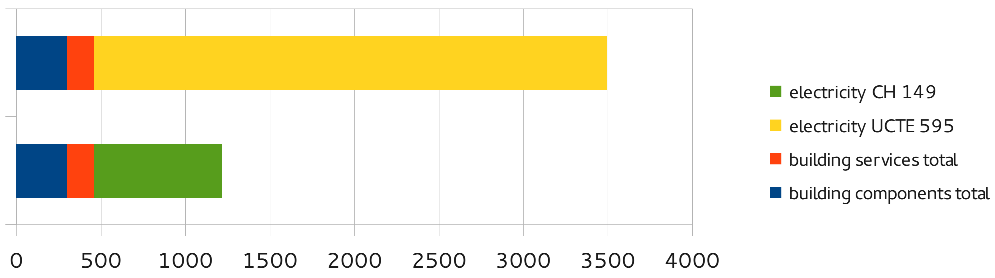

Figure 22: case study 2, overall emissions over lifetime

In case of the UCTE electricity mix a total of 3490 kg CO_2-equiv./m² BRA emission equivalents accumulates over the building's lifetime where 13 % can be ascribed to the physical structure. In case of the Swiss electricity mix the total emissions are 1216 kg CO_2-equiv./m² BRA where 37 % are related to embodied energy. Unlike the case study 1 the total reduction compared to the base case is minor and account only for 3 % in case of the UCTE mix and 5 % in case of the Swiss electricity mix.

Case study 3

Description

This case study combines the measures of case study 1 and case study 2. As base module case study 2 is used with respect to material choice and construction principles. Additionally, the net-zero energy balance as in case study 1 will be achieved. While case study 2 focused mainly on a material approach this case study comprises all aspects of the "building of tomorrow" concept.

Changes to the base case

Starting point are the constructions of case study 2. To reduce the heat loss similar measures as for case study 1 are made. The U-values of the exterior walls and the ceiling to the cold attic are improved from 0.09 to 0.06 W/(m²·K).

Due to the increased heat storage capacity the installed power for heating could be reduced once more to 4.2 kW which is only 55 % compared to the base case. As in case study 1 the roofing tiles on the north and south-facing roof slopes were substituted by photovoltaic modules yielding approximately 9000 kWh of electricity over the year (Fig. 23).

Electricity demand		**Photovoltaics**			**Direct electricity**		
		PV supply	coverage by PV		coverage by grid-el		Off-set el
[kWh]			[kWh]		[kWh]		[kWh]
Jan	-915.2	0.0	0.0	0%	915	100%	0.0
Feb	-820.0	0.0	0.0	0%	820	100%	0.0
Mar	-819.7	327.5	327.5	40%	492	60%	0.0
Apr	-671.3	1090.0	671.3	100%	0	0%	418.7
Mai	-669.7	1614.7	669.7	100%	0	0%	945.0
Jun	-614.6	1756.3	614.6	100%	0	0%	1141.7
Jul	-635.4	1643.4	635.4	100%	0	0%	1008.0
Aug	-635.4	1193.9	635.4	100%	0	0%	558.5
Sep	-614.6	718.7	614.6	100%	0	0%	104.2
Okt	-697.2	407.2	407.2	58%	290	42%	0.0
Nov	-785.2	174.8	174.8	22%	610	78%	0.0
Des	-879.1	48.3	48.3	5%	831	95%	0.0
	-8757.3	**8974.8**	**4798.7**	**61%**	**3958.6**	**39%**	**4176.1**

Figure 23: case study 3, energy supply

The reduced power demand leads also to a slightly reduced net-energy demand but the figures do not differ very much from case study 1.

Results of energy performance calculations

"Simien" results are shown below (Fig. 24).

pos.		*energy demand*	*specific energy demand*
1a	space heating	1937 kWh	12.1 kWh/m²
1b	ventilation heating	343 kWh	2.1 kWh/m²
2	domestic hot water	4765 kWh	29.8 kWh/m²
3a	fans	701 kWh	4.4 kWh/m²
3b	pumps	251 kWh	1.6 kWh/m²
4	lighting	1822 kWh	11.4 kWh/m²
5	equipment	2803 kWh	17.5 kWh/m²
total net energy demand		**12623 kWh**	**78.9 kWh/m²**

Figure 24: case study 3, energy budget

The figures show apparently similarities to case study 1, even though the total net-energy demand is even more reduced to 79 kWh/(m²·a). The increased heat storage capacity is illustrated in the energy demand for the pumps of the heating system which require less than 60 % compared to the lightweight case study 1 building.

Also the results for delivered energy are similar to case study 1 (Fig. 25).

energy source	delivered energy	specific energy demand
direct electricity	5577 kWh	34.9 kWh/m²
el, heat pump	3174 kWh	19.8 kWh/m²
total delivered energy	**8751 kWh**	**54.7 kWh/m²**

Figure 25: case study 3, delivered energy

A slight reduction can be observed due to the demand of the auxiliary systems.

Results of emission inventory

As in case study 1 the installation of photovoltaics dominates the emissions from the building components (Fig. 26).

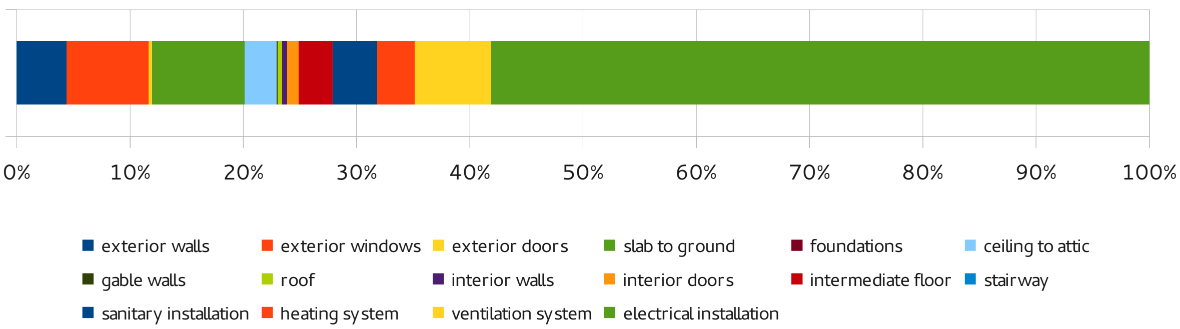

Figure 26: case study 3, emissions from building components and services

Emissions related to embodied energy are 111 % higher than the base case but only 93 % of the case study 1. Emissions from building components account for 28 % of the emissions while the proportion of emissions from building services has increased to 72 %. Although the performance is greatly improved the emissions from the building components account for one eighth less than the emissions from components of the base case. Also the emissions related to the heating system are reduced due to the decreased power demand. The photovoltaic system now accounts for 58 % of the total emissions.

While the slab to ground and the intermediate floor are the same as in case study 2 emissions related to the exterior wall construction show significant differences both compared to the base case and the other case studies (Fig. 27).

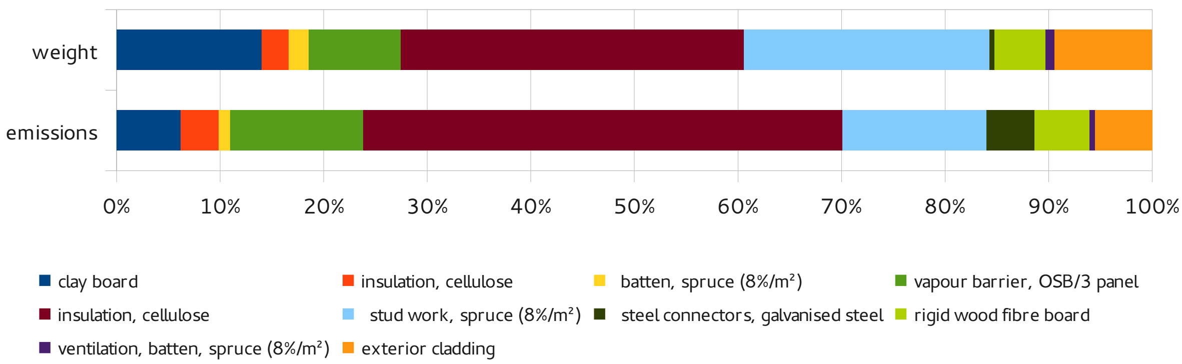

Figure 27: case study 3, exterior wall

Even though the performance is improved the emissions are only 77 % of the emissions in the base case. Compared to the case study 1 with similar performance the emissions are reduced by 39 %. In case study 1 the insulation material mineral wool accounted for only 26 % of the weight but 65 % of the emissions. In case study 3 only 50 % of the emissions can be ascribed to the cellulose insulation even though it accounts for 36 % of the weight.
The reduction of emissions related to building components results in very low total emissions over lifetime (Fig. 28).

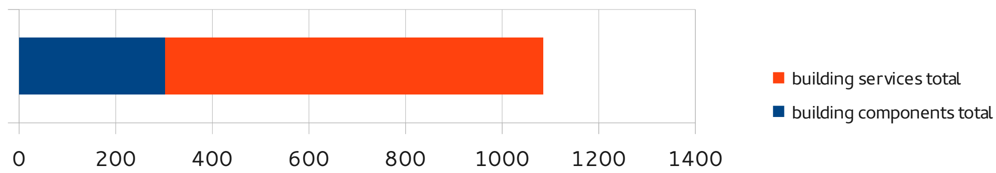

Figure 28: case study 3, overall emissions over lifetime

A total of 1085 kg CO_2-equiv./m² BRA is associated with this case study over 60 years. Compared to the base case with UCTE electricity mix this accounts only for 30 % while in case of the Swiss electricity mix a reduction of 15 % is achieved.

Discussion

Not all case studies could be extensively developed as intended due to limitations in the databases. A comparison and evaluation of the case studies is therefore limited. This shows the importance of a comprehensive database with state-of-the-art materials and products. The limitations of the used databases have become apparent very quickly during the preparation of the case studies. Many aspects and decisions could be identified which influence the results. Those with evidently big impact will be discussed hereafter.
Below the total emissions of the base case and the three case studies for the two examined electricity mixes (Fig. 29, 30).

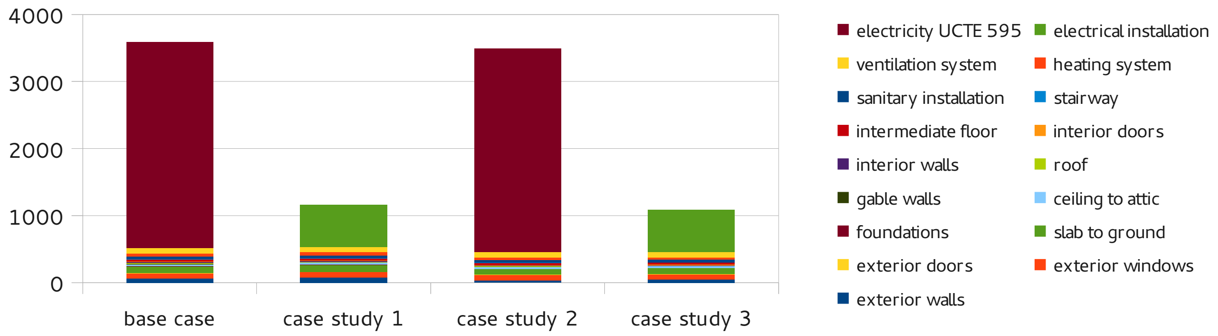

Figure 29: comparison of case studies, UCTE electricity mix

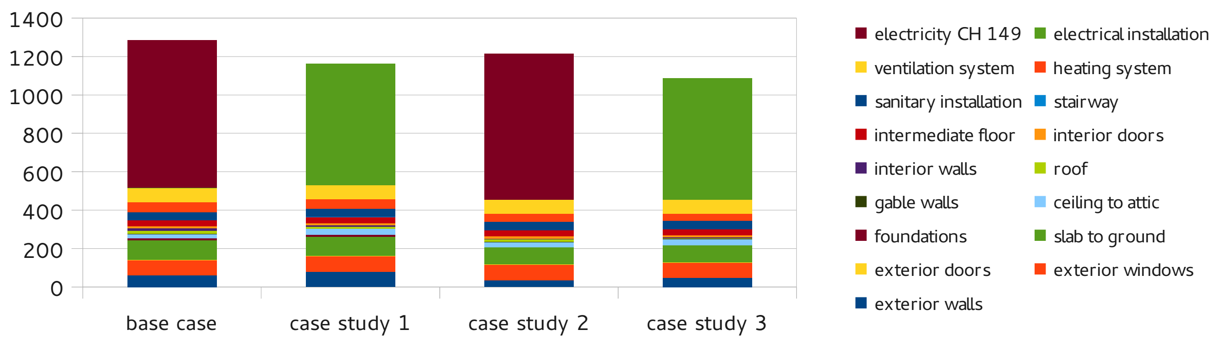

Figure 30: comparison of case studies, Swiss electricity mix

When applying the UCTE electricity mix representing the present ´dirty´ electricity infrastructure clearly most emissions are related to operation. Therefore case studies 2 and 4 where operational emissions can be assumed as zero have significantly lower emissions. Applying the Swiss electricity mix representing a de-carbonised electricity grid the differences are less distinct. And since electricity is also part of the emissions of building materials as electricity factor for the production the results might align even more. Hereby also the location of production gains increased importance.

As mentioned, “Ecoinvent” and the databases derived from it include carbon sequestration in the disposal phase. This cradle-to-gate approach does not allow to appreciate and encourage renewable raw materials and the recycling and reuse of building materials. The difference between case study 2 and the base case can not be elucidated in the total figures. When using “Ecoinvent” only cradle-to-cradle or cradle-to-grave boundary conditions are able to illustrate the impact of environmentally friendly materials. A Zero Emission Building definition intending to achieve a net zero emission balance of embodied and operational energy can not possibly be achieved without renewable materials and cradle-to-cradle conditions which could reduce the emissions from the building materials to zero or less.

Below the inventories of the case studies itemised according to the building components and building services (Fig. 31).

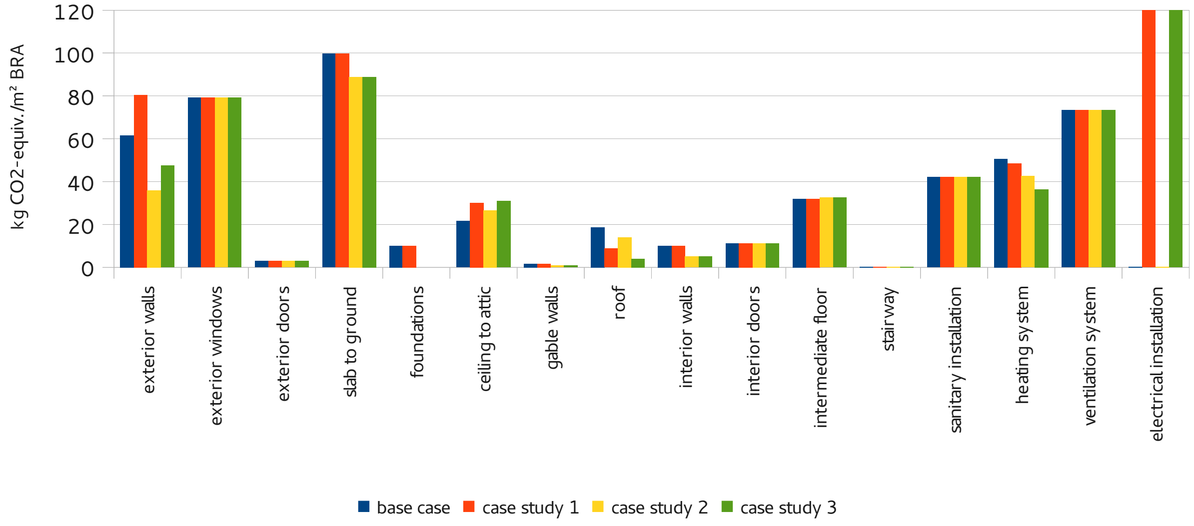

Figure 31: comparison of case studies, emissions from building components and services

Items related to the building envelope account only for approximately 55 % of the emissions in the base case and case study 2, and approximately 25 % in the case studies 1 and 3. Therefore the incorporation of interior components and building services in the inventories seems essential concerning the application of generic models. It can also be seen that when striving for low emission materials and/or installation of emission-intensive energy production facilities like photovoltaics the building services gain more and more impact on the emission balance since the impact of the envelope decreases steadily or even reaches negative values when including possibilities of carbon storage possibilities.

Windows, foundations, slab to ground, floor slabs of the building components and sanitary installation, ventilation system of the building services show high emissions in all four cases. Two main reasons can be identified – lifetime and emission-intensive materials.

Lifetimes of components and services have a crucial impact and must be defined clearly. Especially windows and building services have short individual lifetimes and require replacement when considering the entire building's lifetime. The use of the same material or unit may lead to an overestimation of emissions. However, the certain prediction and application of ´better´ future products and lower emissions due to improved production and a de-carbonised energy supply appears problematic. More important might be the handling of the replaced items. Cradle-to-gate conditions do not allow an appropriate treatment in this case.

Short-lived components also point at the issue of lump packages and assemblies of elements with different lifetimes. In the first case separation into smaller units according to different lifetimes is necessary. While ducts in a ventilation system have an assumed lifetime of 30 years the lifetime of the heat recovery unit might be as short as 10 years. This also raises the question of building integrated building services when building components overlay elements with shorter lifetime, e.g. buried electrical installation (15 years lifetime) inside a wall construction (60 years lifetime).

Materials with high emissions are synthetic materials, plastics, metals, concrete but also cross-laminated timber under cradle-to-gate conditions. Except of concrete these sensitive inputs occur only in small quantities and very thin layers. Concrete is hereby a special case. The heavyweight cement and the aggregates themselves do not contribute high emissions due to the production with low-carbon electricity factors in Switzerland. This can be seen when comparing the slab to ground in the base case and case study 2 which have a fourfold amount of concrete but in total less emissions. More emissions are related to the reinforcement steel which accounts only for 2 % of the entire concrete mix. The quantities and densities of these sensitive elements have to be treated attentively in the inventories. Therefore, further studies of emissions over lifetime should also include the finishes of surfaces as these items are both emission-intensive and frequently renewed.

Conclusions

A comprehensive carbon inventory of emissions related to operation and energy embodied in the building components and building services has been performed. Several alternative highly energy efficient building concepts which can be applicable when striving for Zero Emission Buildings have been investigated. Emphasis of the work was on testing the method of carbon inventories over a building lifetime. Limits were explored and issues revealed.
For the further work it is necessary to proceed towards a clear definition of building concepts like Zero Emission Building to appoint distinctive targets for the research. Regarding the work with generic models the balance between a necessary precision in detail and a universal validity needs to be explored further. Carbon emission inventories over a building's lifetime depend on clear standards and definitions of boundary conditions. Emission inventories can be a powerful tool to define and examine or prove holistic environmentally friendly building concepts.

References

Althaus, H.-J. ed., 2011. *Ökologische Baustoffliste (Version 2.2e)*. [xls] Available at http://www.empa.ch/plugin/template/empa/*/98224 [accessed 15 Nov 2011].

Berge, B., 2009. *The Ecology of Building Materials*. 2nd ed., Oxford: Architectural Press.

Fechner, J., Lipp, B. and Lechner, R., 2002. *ÖKOinFORM Folder 3 – Passivhaus aus nachwachsenden Rohstoffen*. [pdf] Available at: http://www.hausderzukunft.at/hdz_pdf/folder_oekoinform_03_nawaro_passivhaus.pdf [accessed 18 Nov 2011].

Gruppe Angepaßter Technologien ed., 2002. *Planen und Bauen für die Zukunft – Das S-House*. [pdf] Available at: http://www.s-house.at/S-House_Broschuere.pdf [accessed 18 Nov 2011].

Gustavsson, L., Joelsson, A., Sathre, R., 2010. Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building, *Energy and Buildings*, 42 (2010), pp. 230-242.

HAUS der Zukunft, Austrian Federal ministry for transport, innovation and technology ed., 2011. *HAUS der Zukunft – Ziele & Inhalte*. Available at: http://www.hausderzukunft.at/about/index.htm [accessed 11 Dec 2011].

Houlihan Wiberg, A. A-M. and Hestnes, A. G., 2011. Development of a CO2 Emissions Accounting Method for Norwegian Zero Emission Buildings (ZEB). *Proceedings of CISBAT Conference 2010*, Lausanne.

Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren (KBOB) ed., 2011. *Ökobilanzdaten im Baubereich, Stand Januar 2011*. [xls] Available at http://www.eco-bau.ch/resources/uploads/Liste_Oekobilanzdaten_Januar_2011.xls [accessed 15 Nov 2011].

Nordby, A. S. and Miller, F., 2010. Miljøparadokser i Byggebransjen. *Arkitektur N*, 2010/03, pp. 34–39.

NTNU and SINTEF eds., 2007. *ENØK i bygninger – effektiv energibruk*. 3rd ed., Oslo: Gyldendal undervisning.

Passivhaus Institut (PHI) ed., *The Passive House – definition*. Available at: passipedia.passiv.de/passipedia_en/basics/the_passive_house_-_definition [accessed 27 Nov 2011]

Projektfabrik eds., 2002, Building with Renewable Raw Materials, *Forschungsforum 4/2002*. [pdf] Available at: http://www.s-house.at/FOFO_4_2002_engl.pdf [accessed 18 Nov 2011].

Sartori, I., Graabak, I. and Dokka, T. H., 2010. Proposal of a Norwegian ZEB definition: Storylines and Criteria. *Zero emission buildings – proceedings of Renewable Energy Research Conference 2010*. Trondheim: Tapir Academic Press.

Sartori, I. et al., 2010. *Criteria for Definition of Net Zero Energy Buildings*. [pdf] Available at: www.sintef.no/home/Publications/Publication/?pubid=SINTEF+S18793 [accessed 24 Oct 2011].

Sartori, I., Napolitano, A. and Voss, K., 2011. Net Zero Energy Buildings: A Consistent Definition Framework. [submitted to *Energy and Buildings*, October 2011]. Oslo

Voss, K. and Musall, E., 2011. *Net Zero Energy Buildings – International comparison of carbon-neutral lifestyles*. Basel: Birkhäuser