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Relative importance of electricity sources and construction practices in residential buildings: A Swiss-US comparison of energy related life-cycle impacts

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ABSTRACT

Comparisons of buildings in similar climates built in accordance with different regional construction practices and building rating systems can provide useful insights in sustainable design practices. The objectives of this study were: (1) to perform energy related life cycle assessments of a typical LEED-H (Leadership in Energy and Environmental Design for Homes) single-family home in New Jersey (US), and a typical Minergie-P single-family home in Chur, Switzerland; and (2) to assess the effect of rating systems and construction practices on the buildings' environmental impacts. Inventory data was obtained from the Ecoinvent 2.2 database with a replacement of the Western European electricity mix with the US or New Jersey electricity mix for the New Jersey home. The Swiss building performed better regarding non-renewable energy consumption, Global Warming Potential and Acidification Potential mainly due to the geothermal heat pump and the Swiss electricity mix while there was less of a difference regarding Ozone Layer Depletion Potential and Eutrophication Potential. The influence of electricity sources exceeded the effects of longer building life time or the removal of the Swiss basement. Regional building practices, local codes and environmental policies should take the electricity mix into account because it is so important.

1. Introduction

Buildings contribute as much as one third of total global greenhouse gas emissions, primarily through the use of fossil fuels during their operational phase [1]. Due to growing concerns about future energy supply constraints, the design of buildings that minimize their overall environmental burdens and especially energy consumption has garnered increasing interest globally. The approaches vary since for example construction practices differ regionally depending on building codes, governmental incentives, job training, public support and cultural preferences.

The past 20 years have also seen the development of different rating systems that recognize sustainable design in buildings, including Minergie and its passive house application, Minergie-P, in Switzerland and Leadership in Energy and Environmental Design (LEED) in the US [2]. Comparisons of buildings that are designed to comply with different rating systems can provide useful insights in sustainable building design practices. For example, a comparison can explain why generally the operational phase contributes less than 50% to the overall life cycle energy consumption of Minergie-certified homes [3], while this percentage is above 50% in most LEED certified homes [4], even though the majority of both building types are light wood frame buildings.

Comparisons of operational and life cycle energy consumptions of Minergie and LEED certified buildings are scarce [5]. However, LEED certified buildings also conform with ENERGY STAR requirements, and therefore comparisons of homes built to Minergie and ENERGY STAR requirements explain some differences. ENERGY STAR buildings are evaluated by the REM/Rate Home Energy Analysis software that assigns buildings a Home Energy Rating System (HERS) index between 0 for a net-zero building and 100 for a conventional reference building complying with the 2006

Abbreviations: AP, Acidification Potential; AAP, Aquatic Acidification Potential; AEP, Aquatic Eutrophication Potential; BEES, Building for Environmental and Economic Sustainability; CED, Cumulative Energy Demand; GWP, Global Warming Potential; NRE, Non-Renewable Energy; ODP, Ozone Layer Depletion Potential; TA/NP, Terrestrial Acidification/Nutrification Potential.

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International Energy Conservation Code. A comparison of operational energy consumption and life cycle costs of a typical residential home in Indiana, US, complying either with Minergie or ENERGY STAR requirements showed that Minergie buildings are superior regarding energy efficiency due to more extensive insulation, more efficient mechanical equipment and solar heated hot water usage [6]. Based on the energy analysis, a typical new residential home in Indiana received a HERS rating of 98, the ENERGY STAR home of 79, a standard Swiss building of 54 and a Minergie building of 37. The HERS rating of a Minergie-P building would be even lower than that of the Minergie building while a LEED building should receive at minimum the HERS rating of the ENERGY STAR home. However, the comparison also showed that a Minergie home in Indiana is more expensive than an ENERGY STAR home in the short term, although there was a break-even point after more than 40 years assuming an annual energy escalation rate of 3% and a discount rate of 2%.

While this study explains the lower operational energy consumption of Minergie and Minergie-P homes compared to LEED-certified homes it does not address how much the energy consumption in the material placement phase (i.e., raw material extraction, building material manufacturing and refinement, construction) will increase in a Minergie certified home that for example implements superior insulation compared to a LEED certified building (Table 1).

To better understand the energy related life cycle environmental impacts, the objectives of this study are: (1) to perform energy related life cycle assessments (LCAs) of a 317 m^2 (255 m^2 heated) residential building in Monmouth County, New Jersey (US), which was built to meet LEED-H Silver standards and a 406 m^2 (191 m^2 heated) residential building in Chur, Switzerland that was designed to Minergie-P standards; and (2) to assess the effect of different rating systems and construction practices on mainly energy-related environmental impacts. While the New Jersey, US, building is an existing building with a conditioned basement as typical for the region, the Swiss building is a generic building that complies with Minergie-P requirements and which has an unconditioned basement as representative for this region. Chur was chosen as building location for the Swiss building because only a few additional modifications are needed for the building design to obtain certification and because its climate is similar to the climate in New Jersey.

2. Materials and methods

The LCA was conducted in accordance with ISO standards 14040 and 14044 [7,8]. The majority of the inventory data for the Swiss building were obtained from the Ecoinvent 2.2 database [9]. For the New Jersey, US, building, fewer inventory data were available. Most energy, material and emissions data were obtained from Ecoinvent 2.2. Although mainly focused on Western Europe, updates to this database include conditions for other countries, including the US. Where appropriate, the energy mix for the Western European data was replaced with the US or New Jersey energy mix for manufacturing and operation of the building. For datasets not found in Ecoinvent 2.2, datasets were created based on literature data and company information. The LCA was modeled in SimaPro 7.2.3 (PRé, Amersfoort, NL), which incorporates the aforementioned inventory database. An overview of the simulation process and the implemented tools can be found in the supplemental material (Figs. S1 and S2).

2.1. Buildings

The existing four-bedroom two-story single-family house in Monmouth County, New Jersey has a finished basement and a one-car garage on ground level, which is typical for the region. The building, occupied since 2008, has a gross floor area with garage of 317 m^2 and a net floor area of 286 m^2 of which 255 m^2 are heated. This is about 13% above the heated floor area of new single-family homes in the Northeast of the US for 2010 with 225 m^2 (=243 m^2 gross floor area without garage/1.08) [10]. The light wood frame building is designed to LEED-H (LEED for Homes) Silver standards, the most common LEED standard for single-family homes in New Jersey. Electricity and natural gas for heating are provided by the local utility. The building characteristics are provided in Table 2 and the building material inventory in Table 3.

The four-bedroom two-story single-family house in Chur, Switzerland is a typical Minergie-P certified building design, which was provided by a local construction company. The building has a gross floor area with garage of 406 m^2 and a net floor area of 353 m^2 of which 191 m^2 are heated. This is the typical size for a family of four in Switzerland with an average liveable space per person of 44 m^2 in the year 2000 and the assumption that it is already more than 48 m^2 in the year 2013 [11]. It is designed in the typical Swiss two-level approach for Minergie-P buildings, using concrete and brick for the unheated basement and the below ground garage and light wood frame construction for the first and second floors. Heating is provided by a ground-source heat pump and electricity by the local utility. The building characteristics are summarized in Table 2 and the building material inventory in Table 3.

2.2. Environmental impact categories

The following standard impact categories compare the environmental impacts of both buildings: Non-Renewable Energy, Global Warming Potential, Ozone Depletion Potential, Eutrophication Potential, and Acidification Potential. Three different environmental impact methods provided the characterization factors to convert the inventory data to environmental impacts: IMPACT 2002+ [12], Building for Environmental and Economic Sustainability (BEES) [13] and the Cumulative Energy Demand (CED) [9]. Other environmental impacts included in these methodologies such as human toxicity and ecotoxicity were not applied due to the energy emphasis of this study and because there are more uncertainties concerning these impacts [14].

2.3. System definitions, boundaries and data sources

Only the buildings themselves were considered. This includes the foundations, structure, envelope and interior of each building. The lifetime of the US building was estimated by the builder to be between 50 and 75 years. Since the average lifespan for new residential buildings in Switzerland is 65 years [15], this lifetime was chosen for both buildings. It is assumed that the energy mix and materials used for replacements will remain the same during the entire lifetime of the buildings. This is likely to overstate the actual environmental impacts caused during the building's life cycle, as energy production and material manufacturing technologies become more efficient. The following components were not included in this study: furniture, lighting fixtures and appliances, sitework outside the building footprint, landscaping and utilities outside the building. Burdens from building planning and design were beyond the scope of this study.

The environmental impacts were divided by the floor area to account for the different building sizes. Normalizing by gross or net floor area in each building does not account for the fact that a large portion of the Swiss building's interior space is unheated (i.e., basement), and therefore non-habitable. However, considering solely the heated floor area alone penalizes the Swiss building for not heating rooms that do not require heating, such as laundry

Table 1
Comparison of Minergie-P and LEED for Homes.

	Minergie-P [40,41]	LEED for Homes for Climate Zone 4 [42] [a]
Purpose	Energy efficiency standard incorporating passive design and passive solar technologies	Rating system for green buildings
Assessment type	Threshold levels in key performance indicators	Point system with prerequisite points for good practices and optional points for best practices
Energy demand	Weighted energy index accounting for heating, ventilation, hot water, and air conditioning of 30 kWh/m^2 taking losses for extraction, transportation and distribution into account	Home Energy Rating System (HERS) Index of 85 as a prerequisite or lower for optional credits [b]
Renewable energy	Prerequisite	Optional credits
Heating and cooling demand	<60% of legally allowed annual heat demand for new homes (SIA 380/1:2009 [43] limit) or <15 kWh/m^2, max. 10 W/m^2 for air heating	Proper design and sizing of HVAC equipment, HVAC equipment that meets ENERGY STAR requirements and an ENERGY STAR labeled programmable thermostat as prerequisites and additional credits for further improvements. Reduced air duct distribution losses as a prerequisite with optional credits for further reductions
Controlled outdoor air ventilation and indoor air quality	Controlled outdoor air ventilation prerequisite. Heat recovery required. Proof of thermal comfort during summer necessary	Controlled outdoor air ventilation prerequisite. Heat recovery optional. Prerequisite measures to reduce moisture and exposure to indoor pollutants in kitchen and bathroom with optional credits for further improvements. Appropriate distribution of space heating and cooling for thermal comfort as a prerequisite with further improvements for optional credit. Particulate matter reduction in the supply air by a filter with a minimum efficiency reporting value of at least 8 as prerequisite with further improvements for optional credit
Air infiltration	<0.6 h^{-1} air exchange rate at 50 Pa pressure difference	<6.0 h^{-1} air exchange rate at 50 Pa pressure difference mandatory. Optional credits for reduced air exchange rates up to 2.5 h^{-1} air exchange rate at 50 Pa pressure difference
Insulation	20–35 cm (U-factor: <0.15 W/(m^2 K))	Prerequisite: U-factor: 0.15 W/(m^2 K) for ceiling, 0.44 W/(m^2 K) for wood frame wall, 0.30 W/(m^2 K) for floors, 0.44/0.57 W/(m^2 K) for basement walls, 0.57 W/(m^2 K) for slab, 0.44/0.57 W/(m^2 K) for crawl space. Optional credits for exceeding the above by 5% and for efficient application Thermal bypass inspection required
Windows	Triple panes (U-factor for glazing: <0.6 W/(m^2 K))	Prerequisite: U-factor $\leq$ 2.27 W/(m^2 K) (double panes) and a solar heat gain coefficient $\leq$ 0.45. Optional credits up to a U-factor of 1.82 W/(m^2 K) and a solar heat gain coefficient $\leq$ 0.40
Lighting	No requirement for single-family homes	Prerequisite of some ENERGY STAR labeled lighting in high-use rooms with optional points for further upgrades
Water heating		Optional credits for efficient hot water distribution and insulation and efficient domestic hot water equipment
Appliances	Prerequisite, energy-efficient appliances	Optional credits ENERGY STAR labeled appliances
Construction costs	Should not exceed construction costs of a conventional building by more than 15%	

[a] LEED for Homes certification assesses the building performance in 8 categories (innovation and design process, location and linkages, sustainable sites, water efficiency, energy efficiency and atmosphere, materials and resources, indoor environmental quality, awareness and education). Only energy efficiency and indoor environmental quality credits are covered in this table. The maximum LEED points are 136 including 38 points energy efficiency and 21 indoor air quality points.
[b] Range of HERS ratings: 0 (net-zero building) and 100 (conventional reference building).

and mechanical rooms in the basement. Therefore, all alternatives are presented in this study.

2.4. Material placement phase

The material placement phase includes all activities during raw material extraction and refinement, manufacturing of building materials, construction and renovations of the building and transportation activities throughout the material placement phase. The material placement phase also includes avoided activities (impacts) due to the use of reused and recycled materials. The list of building materials for the US building (Table 2), including renovations, is based on construction plans, final invoices, Material Safety Data Sheets, personal communication with the builder and inquiries of manufacturers and trade organizations. For the Swiss building, the list of building materials is based on construction plans, personal communication with the construction company Renggli AG and the Bauteilkatalog (2009) which identifies materials and processes associated with the production of a unit mass or volume of an individual building component for Switzerland. Due to lack of information on the wiring used in each building, typical values for the United States (0.45 kg copper/m^2 floor area) and for Europe (0.3 kg copper/m^2 floor area) were obtained from the Copper Development Association [16] and the European Copper Institute [17], respectively. The estimates for the Swiss building [17] showed good agreement with the findings by Wittmer [18].

The inventory associated with material manufacturing is mainly based on the Ecoinvent 2.2 database, as previously discussed. For concrete and roofing, which are known to be produced in New Jersey, the electricity in the Ecoinvent 2.2 database was replaced by New Jersey electricity, while for materials produced in other states of the US the average US electricity mix was used. The energy mix for New Jersey was assumed as follows (including imports from mainly Pennsylvania): nuclear, 45%; coal, 28%; natural gas, 23%; oil, 2%; hydroelectric, 0.3%; other renewables, 1.7% [19]. The electricity mix for Switzerland (including imports from France, Germany, Italy and the Union for the Coordination of the Transmission of Electricity (UCTE)) was assumed as follows: nuclear, 52.6%; hydropower,

Table 2
Buildings characteristics.

	New Jersey, US	Switzerland
Structure	Light frame wood construction with concrete block walls in the basement. Insulation of block walls: 5 cm closed cell polyurethane spray foam, U-factor: 0.46 W/(m^2 K)	Light frame wood construction with reinforced concrete exterior and brick interior walls in the basement. Insulation of basement walls: 14 cm mineral wool on outer walls
Floors	Reinforced concrete slab in basement, 10 cm, OSB joists and plywood subfloor in 1. and 2. floor Insulation in 1. and 2. floor: 10 cm closed cell polyurethane spray foam, U-factor: 0.24 W/(m^2 K)	Reinforced concrete slab in basement, 20 cm + 5 cm poor concrete; timber joists, chipboard (2.2 cm) and anhydrite (5 cm) subflooring Insulating concrete in basement. Insulation in 1. floor: 10 cm rigid PUR insulation (*U*-factor: 0.21 W/(m^2 K)), in 2 floor: 6 cm mineral wool insulation and 8 cm EPS foam insulation (total *U*-factor approx. <0.28 W/(m^2 K)). In addition, 2 cm EPS foam plates for sound insulation (*U*-factor: approx. <2 W/(m^2 K))
Exterior walls	Wood studs (5 cm × 15 cm, 61 cm o.c.), plywood sheathing, Hardiebacker board siding, gypsum board on interior. Insulation: 10 cm closed cell polyurethane spray foam, U-factor: 0.24 W/(m^2 K)	Wood studs (6 cm × 38 cm), OSB sheathing, timber siding, PE vapor barrier, gypsum board on interior. Insulation: 38 cm mineral wool, *U*-factor approx. <0.1 W/(m^2 K)
Interior walls	Wood studs (5 cm × 10 cm, 61 cm o.c.), gypsum board on both sides	Wood studs, gypsum board (1.25 cm) on both sides
Windows and doors	Windows: Vinyl-clad wood windows, double-glazed, argon-filled (*U*-factor: approx. 2.84 W/(m^2 K)); doors: exterior wood-glass doors and interior wood doors	Windows: three plastic, otherwise aluminum and wood windows, triple-glazed (U-factor: 0.70–0.97 W/m^2 K); doors: exterior wood-aluminum glass and wood-aluminum doors, interior wood doors
Roof	Wood truss roof, plywood sheathing, asphalt fiberglass shingles Insulation of attic floor: closed cell polyurethane spray foam, 10 cm closed cell polyurethane spray foam plus 46 cm cellulose (*U*-factor: 0.09 W/(m^2 K))	Wooden joists, chipboard and plywood sheating, PUR foam insulation (24 cm) with mineral wool (*U*-factor: 0.1 W/(m^2 K)), 12 cm bitumen waterproofing, synthetic fiber and granulated rubber protection layers; green roof with mineral substrate from expanded clay, and gravel
Flooring	Concrete slab basement, bamboo on 1. and 2. floors, ceramic tiles in bathrooms	Concrete slab basement, ceramic tiles in kitchen, pear wood parquet in rest of house
Ceilings	Painted gypsum board	Painted gypsum board
Heating	Radiant floor	Radiant floor
Cooling and ventilation	Central cooling	Central ventilation
HVAC and hot water equipment	Heating and hot water: 1 three-zone, fuel-fired hydronic distribution boiler for radiant heat, 78 kBTU, 95.0 AFUE, 1 300-L dual heat exchanger indirect water heater (can accept solar later), EF = .85 Cooling: 1 air-to-air heat pump, 18 SEER, air handler, Fresh-Air Intake System with HRV, Control: programmable thermostat and real-time energy-feedback system	Heating and hot water: ground-source brine-water heat pump (COP 4.4–4.7), 400-L hot water tank with plain tube heat exchanger and 6 kW auxiliary heater Ventilation: 1 air handling unit
HVAC distribution	Heating: PEX tubing under floor Cooling: galvanized steel ducts. Insulation in attic and garage: (*U*-factor: 0.71 W/(m^2 K))	Heating: Metalplast pipes under floor (aluminum pipe that is lined with PEX and clad with HDPE) Ventilation: Spiro pipes in galvanized iron sheet
Electricity	Regional utility company	Regional utility company

32.1%; coal, 7.8%; natural gas, 4.9%; oil, 1.8%; other renewables, 0.8% [20]. There are material losses during manufacturing and construction. When known, the losses were added to the inventory of materials for the US building. If these losses were unknown, a 5% loss was assumed [21]. For the Swiss house the losses were based on Kellenberger and Althaus [22]. The replacement frequencies for renovation are summarized in Table 4.

Transportation of raw materials to refinement and manufacturing is included in Ecoinvent 2.2. Transportation to the construction site was added. Transportation distances for the Swiss house were based on Binz et al. (2000) (cited in Kellenberger and Althaus [22]) and in a few cases, where the distance was unknown, 45 km were assumed (average of known transport distances weighted by the transported mass). For the US building, the transport distances were known in most cases. In the few cases, where it was unknown, 450 km were estimated (average of known transport distances weighted by the transported mass). During the construction phase, environmental impacts are caused by electricity use for power tools and lighting, and diesel consumption of heavy equipment. Values found in the literature range between 5% and 10% of the total embodied energy [23–25]. Five percent of the total embodied energy, split evenly between diesel and electric equipment as implemented by Scheuer et al. [24], was chosen.

2.5. Operations phase

The operations phase activities include building heating, cooling and ventilation, lighting, and water heating. To be more compatible with the energy consumption of the Swiss building the energy consumption of the New Jersey, US, building was determined with the REM/Design™ Software instead of using the actual energy consumption. Based on the model the average yearly consumption of natural gas is 75.2 kWh/(heated floor m^2 × year) and of electricity 30.0 kWh/(heated floor m^2 × year). The maximum allowable electricity consumption for space heating of 15 kWh/(heated m^2 × year) in accordance with the Minergie P standards was assumed for the Swiss building (see Table 1). The hot water is provided by the same ground source heat pump. The electricity consumption for all other uses was estimated based on the Swiss national average, which is 4,500 kWh/year for a single-family

Table 3
Life cycle masses.

Switzerland	Initial (replacement) [kg]	New Jersey, US	Initial (replacement) [kg]
Concrete, reinforced	302,608 (0)	Concrete blocks	101,951 (0)
Anhydrite	19,769 (0)	Poor concrete	55,850 (0)
Gravel	18,800 (0)	Gravel	29,724 (0)
Timber	15,554 (4,578)	Drywall	10,496 (12,245)
Brick	13,198 (0)	Cement	8,857 (0)
Steel	11,413 (2,260)	Timber	8,457 (870)
Concrete, non-reinforced	9,690 (0)	Plywood	4,959 (0)
Ceramic tiles	5,112 (0)	Exterior siding	3,450 (3,450)
Cement	4,127 (0)	Steel	3,106 (2,012)
Expanded clay	3,648 (0)	OSB	2,847 (0)
Bitumen	3,437 (4,010)	Cellulose fiber insulation	2,735 (820)
OSB	3,052 (0)	Asphalt shingles	2,251 (3,602)
Plaster	2,589 (3,021)	PUR	1,847 (565)
Particleboard	2,304 (1,897)	Fiberboard	894 (1,026)
Mineral wool	2,094 (1,339)	Bamboo flooring	865 (865)
Drywall	2,021 (2,358)	Fiber-reinforced plastic	769 (0)
Glass	1,998 (2,331)	Glass	628 (873)
PS	1,921 (2,241)	Bitumen	593 (115)
Plywood	1,749 (2,041)	Glue laminated timber	503 (0)
PUR	1,188 (1,386)	Ceramic flooring	415 (0)
PE	866 (842)	PE	394 (643)
Parcquet flooring	550 (550)	Aluminum	390 (483)
Aluminum	330 (386)	Ceramic fixtures	321 (96)
Fiberboard	310 (352)	Paint	306 (2,112)
Cast iron	283 (330)	PVC	145 (213)
Paint	182 (1,080)	Copper	136 (201)
Ceramic fixtures	165 (49)	PS	135 (222)
PVC	125 (179)	Rubber	38 (50)
Copper	114 (196)	Mineral wool	33 (66)
PP	62 (72)	Zinc	3.6 (3.1)
Rubber	57 (76)	Nylon	2.4 (1.5)
Glass fiber wallpaper	40 (25)		243,100 (30,534)
Nylon	13 (15)		
Bentonite	8.0 (0)		
Zinc	3.8 (4.4)		
	429,381 (31,620)		

Table 4
Replacement frequencies.

Building shell and structure			Mechanical, electrical, plumbing			Building interior and finishes		
Component	US	Swiss	Component	US	Swiss	Component	US	Swiss
Concrete blocks	Life[a]	Life[b]	Air Handling Unit and Controls	20[e]	20[e]	Drywall	30[b]	30[b]
Poured concrete	Life[a]	Life[b]	Heating Water Pipes	25[e]	–	Interior Doors	30[e]	30[b]
Structural Wood	Life[a]	Life[b]	Heating Equipment	30[e]	30[b]	Wooden Flooring	½ Life[k]	½ Life[k]
Exterior Wall Sheathing	Life[a]	Life[b]	Plumbing Fixtures	35[e]	35[e]	Paint	5[e]	5[e]
Roof Truss	Life[a]	Life[b]	Electrical Wires and Boxes	25[e]	25[e]	Ceramic Tiles	Life[j]	Life[j]
Floor joists	Life[a]	Life[b]	Stainless Steel Piping	–	30[e]			
Exterior Siding	50[c]	½ Life[b]	Polyethylene Piping	50[k]	50[k]			
Brickwall	–	Life[b]	Air Source Heat Pump	20[f]	–			
Asphalt Roofing	25[a]	–	Ground Source Heat Pump	–	20[g,h,i]			
Polyurethane Insulation	50[d]	½ Life[b]	Spiro Pipes	–	25[b]			
Polystyrene Insulation	–	30[b]						
Glass Wool Insulation	–	40[b]						
PE Vapor Barrier	–	40[b]						
Bitumen Sealing	–	30[b]						
Windows	40[e]	30[b]						
Exterior Doors	40[e]	30[b]						
Fiberboard	–	40[b]						

[a] Builder (personal communication).
[b] Bauteilkatalog [44].
[c] JamesHardie [45].
[d] BASF [46].
[e] Dell'Isola and Kirk [47].
[f] Shah et al. [37].
[g] Saner et al. [48].
[h] A.M. Omer [49].
[i] Nagano et al. [50].
[j] Scheuer et al. [24].
[k] Some materials are too new to foresee their lifetimes, therefore assumptions had to be made. Polyethylene pipes are assumed to last 50 years, which corresponds to twice the typical manufacturer warranty. For pear wood and bamboo flooring, it is assumed that one replacement takes place during the building lifetime and that regular maintenance (sanding and refinishing) is performed every 10 years.

home without electric boilers and two tenants [26] which would be 20.5 kWh/(heated floor $m^2 \times$ year) for the Swiss building.

The annual average temperature for Chur is 10.0 °C [27], while it is 11.4 °C in Monmouth County, New Jersey (approximated ONJSC data for Long Branch Oakhurst station). To confirm that these average temperature differences do not result in an unfair comparison between the buildings, the operational energy consumption of the New Jersey house (modeled by the REM/Design™ Software) was compared to the modeled operational energy consumption of the same house but located in Elkins, West Virginia. Based on temperature and insolation, Elkins is the location in the US with the most similar climate to Chur, Switzerland (Broccoli, personal communication). Due to the temperature difference the New Jersey house uses 4.8% less operational energy (=5.4% heating − 1.4% cooling + 0.8% hot water) at the Monmouth County, New Jersey, location than at the Chur, Switzerland location (based on the Elkins, West Virginia data). If the Swiss house is located in Monmouth County, New Jersey cooling might need to be provided to have the same comfort level as in the New Jersey house. We assume that the radiant floor can provide the cooling if the Swiss home would be located in New Jersey, US and the tenants accepted the somewhat larger temperature swings Europeans are accustomed to. In this case, the heat pump is off, but the circulation pumps are operating.

2.6. Decommissioning phase

The decommissioning phase includes all activities related to the deconstruction and demolition of the building, onsite sorting and transportation of materials and wastes and the final disposal of the wastes. Conventional practices usually result in many materials being landfilled. However, the building can be selectively disassembled and 70–90% of the materials can be salvaged [28,29]. Deconstruction is two to 10 times more time consuming than conventional demolition [30] because many assemblies have to be manually dismantled, but heavy equipment is used less. Since both buildings have sustainable design labels, it is assumed that a large portion of the materials are salvaged during decommissioning. How deconstruction and recycling practices will change in the future is difficult to foresee. Therefore, a best case scenario was assumed for both buildings, in which the majority of the recyclable materials are selectively disassembled and reused or recycled: glass, drywall, window frames, concrete blocks and poured concrete, structural wood, and electrical wiring.

The actual energy consumption during decommissioning is not known. Energy consumption for deconstruction and demolition, transport of materials and wastes and landfilling or incineration of the waste were included. Processing in the material recovery facility is considered outside the boundary. It is assumed that the deconstruction and demolition takes 10 days, that a hydraulic excavator is needed for one day (189 L/d diesel consumption) and power tools (7.6 L/d gasoline consumption) for 10 days (J. Vinch & Sons Demolition Contractors & Recyclers, personal communication) and that the distance to the local landfill and material recovery facility is 18 km for the New Jersey building and 7 km to the local incinerator and the material recovery facility for the Swiss building.

2.7. Uncertainty analysis and scenario analyses

In order to assess the reliability of the results a Monte Carlo uncertainty analysis with 1,000 runs was conducted. The distribution of the inventory data are included in the inventory databases.

As part of a sensitivity analysis, three scenarios were assessed which were believed to have an effect on the environmental impacts. It is known that the energy grid has a large impact on the environmental impacts. Therefore, as a first scenario an LCA of each building was run with the other region's electricity mix. As a second scenario, life spans of 40 and 90 years were assessed. As the third scenario, a LCA of the Swiss building without the basement and the garage was modeled. Large basements as storage and mechanical rooms and an underground garage are a typical regional building practice in Switzerland, but not in New Jersey, US. The basement and the underground garage increase the mass of the construction materials especially concrete.

3. Results and discussion

The energy-related life cycle environmental impacts are discussed below by impact category. The Swiss home performed better than the New Jersey, US building in all categories for the total life cycle environmental impacts for both the entire building and when normalized by the net floor area. Therefore, in the following discussion the results for all impact categories and life cycle phases are mainly presented on a livable (heated) floor area basis, which penalizes the Swiss building due to the unheated basement. The results for the entire building or normalized by the net floor area are only discussed for those categories and life cycle phases where the choice of the normalizing floor area affected the results. Since most results determined by the BEES impact method are very similar to the results based on the IMPACT 2002+ method, the BEES results are mainly presented in the supplemental material. Results affected by the choice of the impact method are discussed as part of the uncertainty analysis.

3.1. Environmental impacts

3.1.1. Primary energy consumption

The life cycle primary energy consumption for the New Jersey, US, case study building was 16,830 kWh/heated m^2 according to the CED methodology, while the Swiss building's consumption was 12,762 kWh/heated m^2 (Table 5). The majority of the energy consumption in the New Jersey house was associated with the operational phase (79.5%), whereas for the Swiss home the energy consumption was split nearly evenly between the operational (49.2%) and the material placement (49.1%) phases with additional 1.7% consumed during the decommissioning phase. This split between material placement and operational phases confirms previous assessments for a Swiss low energy building with passive house features, ground source heat pump and solar energy [3].

Material placement phase. The primary energy consumption in the material placement phase for the New Jersey house was 0.86 GWh eq. (=2,726 kWh/gross floor m^2 = 3,016 kWh/net floor m^2 = 3,389 kWh/heated floor m^2) (Fig. 1, Table 5). The Swiss building consumed more primary energy in the material placement phase with 1.20 GWh eq. (=2,947 kWh/gross floor m^2 = 3,395 kWh/net floor m^2 = 6,265 kWh/heated m^2). This was mainly due to the installation of more insulation, the bituminous waterproofing required for the building's green roof, the triple pane windows and more concrete in the basement, the foundation and the below ground garage. However, on a per metric ton building mass basis the New Jersey building consumed more primary energy with 3,150 kWh/metric ton compared to the Swiss building with 2,600 kWh/metric ton. The longer transportation from the manufacturer for the New Jersey home contributed to this difference. However, even though the building frame was transported from the Pacific Northwest to the East coast of the US, only 4.3% of the primary energy consumption in the New Jersey house in the material placement phase is consumed for transportation from the manufacturer to the construction site and therefore longer transportation distances explain only part of the difference. The more important reason is that a large portion of the Swiss building's additional building mass is concrete in the unheated basement, which

Table 5
Life cycle impacts for the Swiss building and the New Jersey, US, building based on the CED and the IMPACT 2002+ methods and normalized by the heated floor area.

	Total		Material placement phase		Operational phase		Decommissioning phase	
	US	Swiss	US	Swiss	US	Swiss	US	Swiss
CED								
	16,830	12,762	3,389	6,265	13,376	6,278	65	219
IMPACT 2002+								
NRE [kWh primary]	16,376	10,487	2,596	4,836	13,716	5,433	64	218
GWP [kg CO_2 eq.]	2,730	1,386	553	852	2,147	279	30	255
ODP [g CFC-11 eq.]	0.34	0.31	0.07	0.27	0.27	0.04	0.00	0.00
AEP [g PO_4^{3-} eq.]	327	328	199	239	127	84	1	5
AAP [kg SO_2 eq.]	12.7	6.3	3.9	4.8	8.6	1.2	0.2	0.3
TA/NP [kg SO_2 eq.]	36.1	27.2	17.3	21.7	18.0	3.5	0.8	2.0

is not necessarily a material with the highest energy demand in the material placement phase.

If only the non-renewable primary energy is included the New Jersey house consumed 2,067 kWh/gross floor m^2 (=2,286 kWh/net floor m^2 = 2,569 kWh/heated m^2) and the Swiss house 2,249 kWh/gross floor m^2 (=2,592 kWh/net floor m^2 = 4,782 kWh/heated m^2).

Another term used for the primary energy consumption during the material placement phase is embodied energy. Dixit et al. [31,32] presented an average embodied energy for several residential case study buildings of 1,529 kWh/gross floor m^2 with a standard deviation of 433 kWh/gross floor m^2 which is lower than the values found in the current case study. Similarly, the study by Citherlet and Defaux [3] who determined an annual embodied energy of 28 kWh/gross floor m^2 (=1,400 kWh/gross floor m^2 for a 50-year building life time) for a code building, a Minergie building and a building with passive house features in Switzerland. However, it needs to be noted that the embodied energy for the renewable energy systems was not included in the embodied energy because it could not be separated from the operational energy. Generally, it is very difficult to compare the embodied energy of different buildings unless they are in the same region, are built to similar specifications and their embodied energy is calculated the same way regarding transportation, renewable energy consumption or the decommissioning phase [31,32]. Since there is no generally accepted methodology to calculate the embodied energy it is challenging to draw conclusions in comparison to other studies. The CEDs for both buildings in this study were determined based on the same methodology and therefore at least their comparison is valid.

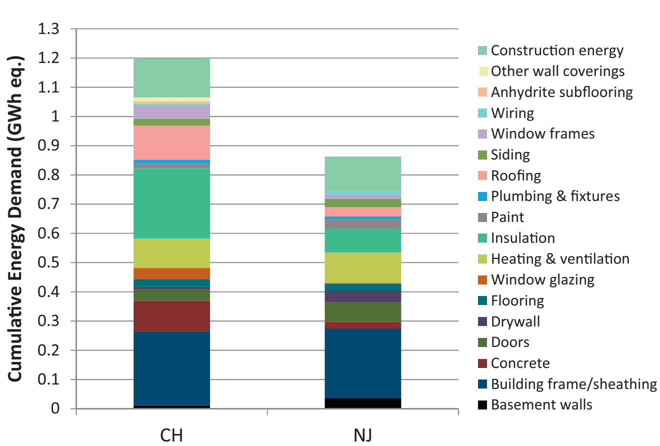

Fig. 1. Contribution of different materials and processes to the Cumulative Energy Demand (CED) of the Swiss (CH) and the New Jersey, US (NJ) building in the material placement phase.

Operations phase. The majority of the life cycle energy use of most buildings occurs in the operation phase due to the energy required for heating and cooling as well as the electricity use for lighting and appliances. The New Jersey building consumed 13,376 kWh/heated m^2 life cycle primary energy (Table 5), or 79.5% of the life cycle primary energy consumption of the building during the operational phase. This energy was consumed for the provision of both natural gas for space heating, water heating and appliances, and electricity for space heating, cooling, lighting and appliances. Over the 65-year lifespan, the building consumed 30.0 kWh/(heated m^2 × year) in electricity and 75.2 kWh/(heated m^2 × year) as natural gas. Based on the gross floor area excluding the garage, the yearly energy consumption is 94.8 kWh/(m^2 × year), which proved to be more energy efficient than the average Northeast detached single-family building home, which consumes 139 kWh/(m^2 × year) [33]. However, this is close to a Swiss code building located north of Lausanne which consumed 98 kWh/(heated m^2 × year) [3].

Due to the Swiss building's very high energy efficiency standards its life cycle energy consumption in the operation phase was much lower, 6,278 kWh/heated m^2 (Table 5, 49.2% of the life cycle energy consumption), that is, less than half of the value for the New Jersey, US, building. As previously indicated, this energy consumption is based on the maximum allowable electricity consumption in accordance with the Minergie-P standard of 15 kWh/(heated m^2 × year) and an electricity consumption for all other purposes of 20.5 kWh/(heated m^2 × year) (=11.1 kWh/(net floor m^2 × year). The reason for the low operational energy consumption of the Swiss building is the ground source heat pump, which extracts heat from the ground to provide space heating in the building and which avoids the natural gas consumption of the New Jersey building. The energy consumption of the Swiss building is close to the final energy demand of a Minergie-certified building (39 kWh/heated m^2 × year), but higher to the final energy demand of a low-energy building with passive house design features and solar power in Lausanne, Switzerland (11 kWh/heated m^2 × year) [3].

Decommissioning phase. The energy consumption during the decommissioning phase is minimal compared to the other phases, with 65 kWh/heated m^2 (0.4% of the life cycle energy consumption) for the US building and 219 kWh/heated m^2 (1.7%) for the Swiss building (Table 5). The higher consumption in the Swiss building can mostly be contributed to the almost double mass of the Swiss building requiring demolition.

3.1.2. Global Warming Potential

The life cycle GWP for the New Jersey, US, case study building is 2,730 kg CO_2 eq./heated m^2 based on the IMPACT 2002+ method (Table 5). This was much higher than for the Swiss building, which had a life cycle GWP of 1,386 kg CO_2 eq./heated m^2. Life cycle GWP is mainly caused by CO_2 releases during the combustion of fossil fuels and, therefore, follows a similar pattern as the non-renewable

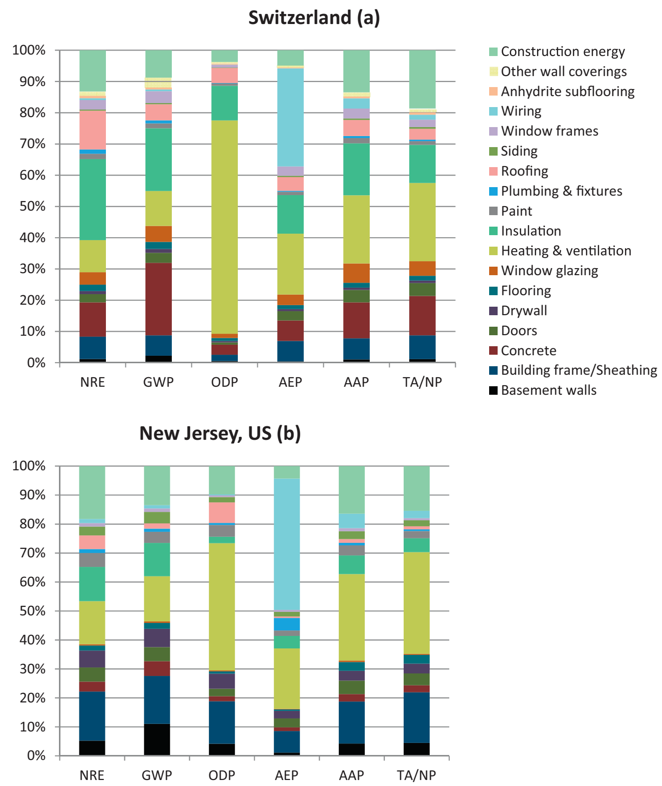

Fig. 2. Contribution of different materials to the material placement phase impacts of the Swiss (a) and the New Jersey, US (b) building according to IMPACT 2002+. NRE = Non-Renewable Energy; GWP = Global Warming Potential; ODP = Ozone Layer Depletion Potential; AEP = Aquatic Eutrophication Potential; AAP = Aquatic Acidification Potential; TA/NP = Terrestrial Acidification/Nutrification Potential.

energy consumption for an electricity mix with major fossil fuel contribution. This applies to the New Jersey, US, case study building.

For the New Jersey, US, building, among the main contributors to the GWP in the material placement phase were the building frame/sheathing, the HVAC system, the construction energy, the insulation and the basement walls (Fig. 2). As individual processes especially the clinker production for the basement walls, the concrete and the siding (11.4%) and the diesel burned during wood harvesting and construction were the largest contributors (7.9%). The majority of the GWP in the operational phase was due to the combustion of natural gas for heating and fossil fuels for electricity generation. The GWP in the decommission phase was small (1.1%) and mostly caused by diesel burnt during building deconstruction (Fig. 3 and Table 5).

The Swiss case study building did not follow the pattern of the non-renewable energy consumption, with about 61.3% of the life cycle GWP (=31.7% if normalized by the GWP of the New Jersey building) occurring in the material placement phase according to the IMPACT 2002+ method (Fig. 3 and Table 5). This is mainly caused by the much lower GWP in the operational phase due to the electricity mix of Switzerland being mostly composed of renewable hydropower and nuclear energy, which do not directly release CO_2. The main contributors to GWP in the material placement phase (Fig. 2) were the production of concrete and cement materials, insulation, the heating and ventilation system, as well as the combustion of diesel for heavy machinery during construction. A large proportion of the life cycle GWP for the Swiss building (18.4% = 9.3% if normalized by the GWP of the New Jersey building), however, was released during the decommissioning phase. This is due to the preferred waste treatment method in Switzerland, in which all combustible wastes are incinerated. Thus, the combustion of the building's insulation and bituminous roof sealing materials are major contributors to the Swiss building's GWP.

The comparability of life cycle GWP of these buildings to the GWP of other buildings reported in the literature is closely related to the operating energy and the electricity mix. Thus, the yearly GWP for the Swiss case study building (10 kg CO_2 eq./gross floor $m^2 \times$ year) is the same as for the Minergie-certified and low-energy passive houses in Switzerland (approximately 10 kg CO_2 eq./gross floor $m^2 \times$ year). The GWP of the New Jersey, US, building normalized by year (34 kg CO_2 eq./(gross floor $m^2 \times$ year) was higher than that of the code building in Switzerland (approximately 27.5 kg CO_2 eq./gross floor $m^2 \times$ year) [3]. As found in previous studies [4,24,34], impacts associated with the decommissioning phase in the US were negligible compared to the impacts during the other life cycle phases. On the other hand, due to the incineration of all combustible waste in Switzerland, the decommissioning phase was one of the main contributors to the Swiss home's GWP, and was generally a much more important contributor to the life cycle emissions than for the New Jersey, US, building. Avoided electricity and heat production is accounted for, but in Switzerland an electricity mix high in nuclear power and hydropower is replaced. In addition, in the Ecoinvent 2.2 database all emissions from incineration are allocated to the incineration and not the electricity and heat production. Major contributors to GWP in the decommissioning of the Swiss house are the building envelope insulation and the roof.

3.1.3. Ozone Layer Depletion Potential

The life cycle ODP for the New Jersey, US, case study building was 0.34 g CFC-11 eq./heated m^2 and for the Swiss case study building 0.31 g CFC-11 eq./heated m^2. These ODPs are generally very low.

In both case studies, the refrigerant used in the heating and cooling systems was a major contributor in the material placement phase (Fig. 2). The refrigerants themselves do not have any ODP, but in the production some ODP releasing compounds were released. In the New Jersey building, R-410a (a mixture of R-32 and R-125) was used, which accounted for 7.6%. In the Swiss case study building, the refrigerant was R-407c (a mixture of R-32, R-125 and R-134a), which accounted for 56.6% of the life cycle ODP mainly from R-134a. Since R-32 and R-125 were not in the Ecoinvent database, these processes had to be created and therefore have a larger uncertainty.

3.1.4. Eutrophication Potential

The IMPACT 2002+ method determined 328 g $PO_4{}^{3-}$ eq./heated m^2 for the Swiss building and 327 g of PO_4 eq./heated m^2 for the New Jersey, US, building (Table 5). The material placement phase is the main contributor in the Swiss case building, accounting for 73%. For the New Jersey, US, building, the operations phase had a larger influence, although the material placement phase still contributed 61%. The most important contributors in all cases were the disposal of spoil from lignite and coal mining, and of sulfidic tailings, which collectively accounted for 80–90% of the emissions.

While the Swiss electricity mix does not rely on generation from coal, electricity imports (particularly from Germany) include a substantial amount of coal-generated electricity. In addition, any materials manufactured outside of Switzerland were also produced using foreign electricity mixes. Ten percent of the life cycle Aquatic Eutrophication Potential of the building can be traced to the manufacturing of materials using electricity produced using the UCTE grid mix. Thus, the disposal of lignite spoil accounted for 33% of the emissions. In addition, the disposal of sulfidic tailings, mainly from copper production, was also a significant contributor to eutrophication, accounting for 35% of the life cycle emissions.

A similar trend was observed for the New Jersey, US, case study building. Given the higher share of coal in the local electricity mix and the higher use of copper in this building, however, the share corresponding to each of these processes was even larger. Thus, the

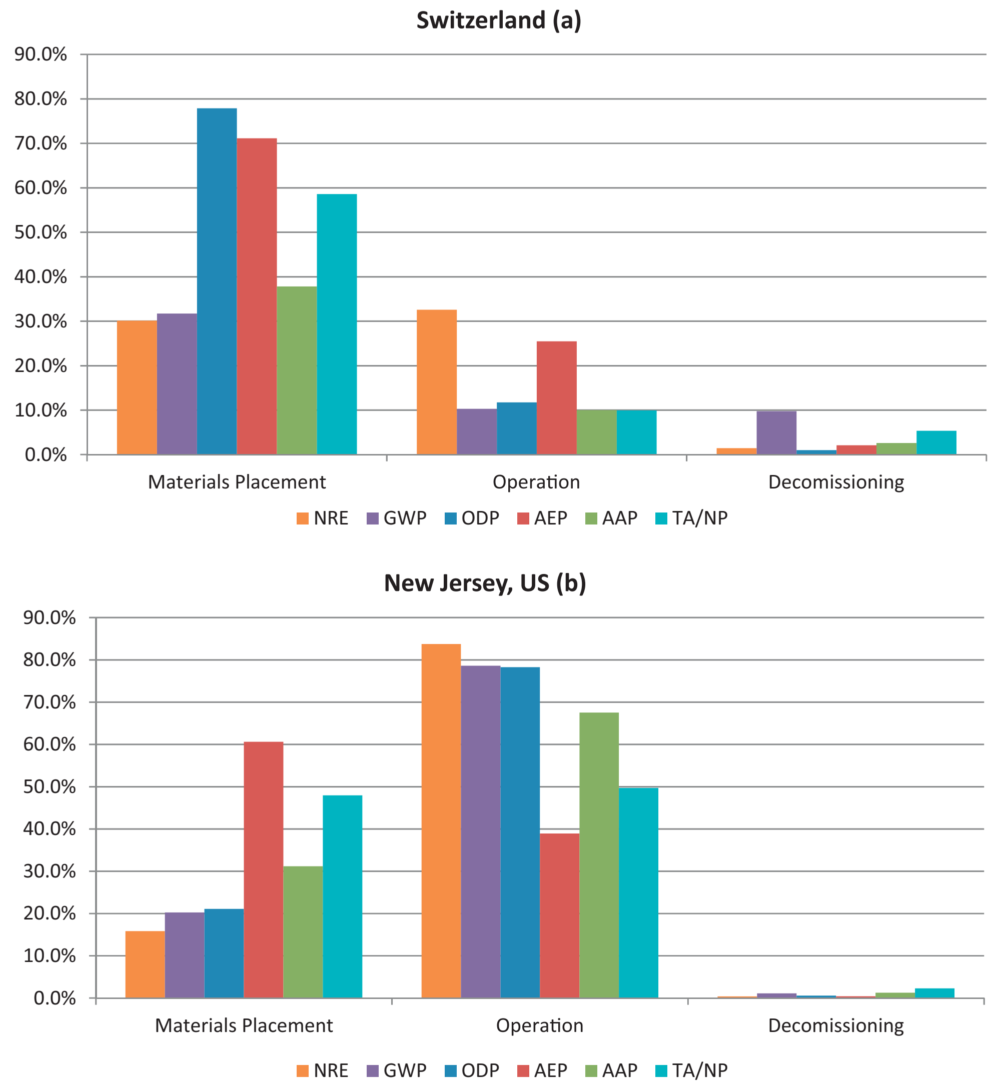

Fig. 3. Life cycle impacts based on the IMPACT 2002+ method for the Swiss building (a) and the New Jersey, US, building (b) for the material placement, the operational and the decommissioning phase (normalized based on the New Jersey, US building).

disposal of spoil from coal mining accounted for 44% of the life cycle impacts, while the disposal of sulfidic tailings accounted for 40%.

It is worth noting that the Ecoinvent process for sulfidic tailings disposal is still very limited, and uses only one dataset for any type of sulfidic tailings deposit [35]. Thus, a high degree of uncertainty is involved when utilizing this data. The sensitivity analysis included in this study is, therefore, of key importance to validate the results obtained.

3.1.5. *Acidification Potential*

The IMPACT 2002+ impact method separates the life cycle AP into Aquatic Acidification Potential (AAP) and Terrestrial Acidification/Nutrification Potential (TA/NP). For the New Jersey, US, building the life cycle AAP was 12.7 kg SO_2 eq./m^2, almost twice as much as for the Swiss case study building, which was 6.3 kg SO_2 eq./heated m^2 (Table 5). The TA/NP for the New Jersey, US, case study building was 36.1 kg SO_2 eq./heated m^2, while the Swiss building's TA/NP was 27.2 kg SO_2 eq./heated m^2.

For the New Jersey, US, building, SO_2 (69%) and NO_x (22%) emissions to air accounted for the majority of emissions contributing to AAP. The most important contributors to these emissions were hard coal and natural gas combustion for electricity generation and space heating. In the Swiss case study building, the main contributors to the AAP were SO_2 (49%) and NO_x (39%). The majority of these emissions originated in the production of electricity (22%), the operation of diesel equipment for construction and deconstruction (14%), and the production of insulation materials (13%). The Terrestrial Acidification/Nutrification Potential for the Swiss case study was mostly caused by NO_x (71%), SO_2 (11%) and ammonia (18%) emissions. The major processes generating these emissions were the operation of diesel equipment for construction and deconstruction (22%), electricity production (14%), and the manufacturing of heating and ventilation equipment (20%).

All acidification impacts followed the Global Warming Potential in each phase of the life cycle. Thus, the majority of the acidification impacts associated with the Swiss building occurred during the material placement phase, whereas the New Jersey, US, case study's acidification impacts occurred mainly during the operation phase.

3.1.6. *Uncertainty analysis*

The Monte Carlo analysis determined the probabilities for each environmental impact, and whether the impact of the New Jersey building, normalized by heated area, was lower than or equal to the impact of the Swiss building or vice versa.

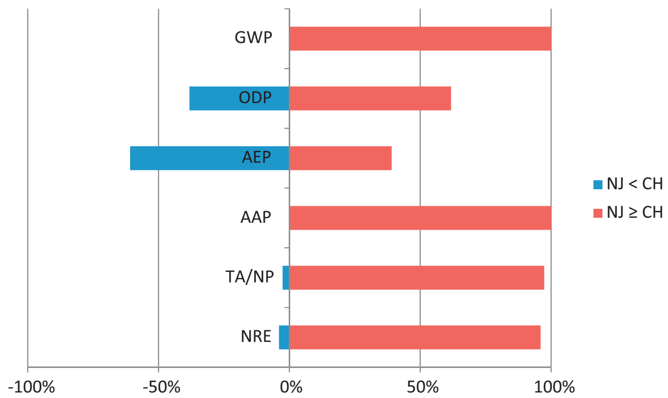

Fig. 4. Uncertainty analysis for the New Jersey, US (NJ) and the Swiss (CH) building. For each category, the probability that the impact of the New Jersey building is lower or higher than the Swiss is shown (normalized by heated area). Monte Carlo simulation, 1000 runs, confidence interval 95%.

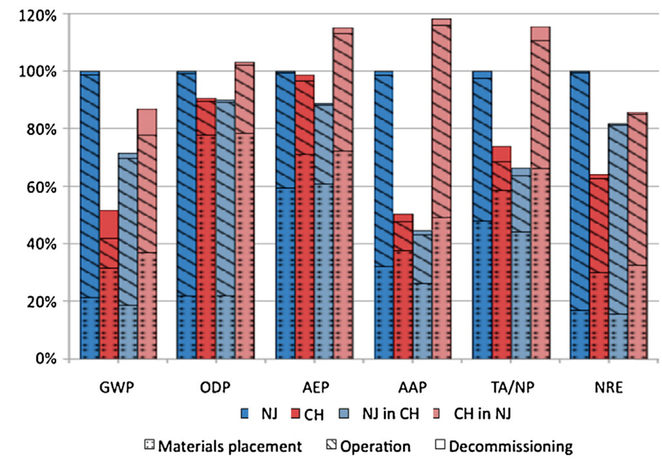

Fig. 5. Normalized life cycle impacts for the two case study buildings as is and with switched electricity mixes (IMPACT 2002+).

The results of the uncertainty analysis confirmed the previous results for NRE, GWP, AAP and TA/NP with very high probabilities that the impacts of the Swiss building were lower (Fig. 4). With regards to ODP, the Swiss case study had higher impacts in about 30% of the runs. This share is considered to be relatively low [36], still confirming the higher impact of the New Jersey building. For AEP, however, the results of the Monte Carlo simulation demonstrated that the Swiss case study building had higher impacts in about 60% of the runs. Nonetheless, given the relatively small difference between the probabilities of both buildings, no clear statement can be made in favor of either case.

Generally, both impacts methods (IMPACT 2002+ and BEES) gave the same results with the exception of ODP (see BEES results in supplemental material). The order of magnitude higher impacts for ODP according to IMPACT 2002+ was caused by the fact that the IMPACT 2002+ method considers additional compounds contributing to the depletion of the ozone layer. In particular, CFC-114, a compound used during uranium enrichment, is included in the IMPACT 2002+ method, but not in the BEES impact method. Since both buildings relied on electricity produced in part by nuclear energy, the ODP for both was higher according to IMPACT 2002+ method. While the Swiss energy mix contains a higher share of nuclear energy, the New Jersey, US, building consumed more electricity during its entire life cycle. In most cases, the majority of the impact was due to the material placement phase (Fig. 3 and S4 in the supplemental material), with 85.9% according to IMPACT 2002+ and 88.6% according to BEES for the Swiss case study building, and 78.4% according to BEES impact method for the New Jersey, US, case study building. According to IMPACT 2002+ method, however, 77.3% of the impact occurs in the operations phase for the New Jersey, US, case study building. The cause was releases of HCFC-22 and Halon 1211 during the transportation of natural gas.

3.2. Scenario analyses

3.2.1. Effect of electricity mix on environmental impacts

It is well known that the electricity mix affects energy related environmental impacts [3,37,38]. To assess if the Swiss building performed better due to the construction practices or the electricity mix the electricity mixes of the two buildings were switched.

The New Jersey, US, building performed on a per heated area basis as well as or better than the basic Swiss case study building when the Swiss electricity mix was substituted for the New Jersey electricity mix (Fig. 5) indicating that the Swiss electricity mix plays an important role in the low environmental impacts of the Swiss building. For example, GWP of the New Jersey building on a per heated floor area basis with a Swiss electricity mix was reduced by 29%. Conversely, the environmental impacts of the Swiss building were generally worse with the New Jersey electricity mix. For example, the GWP of the Swiss building on a per heated floor area basis with the New Jersey electricity mix increased by 71%. However, GWP of the Swiss building on a net floor area basis with a New Jersey electricity mix was still 47% lower than the New Jersey building with the New Jersey electricity mix. The electricity mix was changed for both the manufacturing of the building materials as well as for the buildings' operational energy. The latter was more sensitive to changes in the electricity mix, because the majority of the electricity consumption of the buildings occurred in the operational phase.

Given that the electricity mix is not a factor that a builder can influence; in New Jersey, reducing a building's operational phase energy consumption is an important measure for the building to perform better over its entire life cycle. For the Swiss building, on the other hand, due to the geothermal energy and the lower impact of the country's electricity mix the impact of the operational phase is already low and a reduction in the material placement phase might be more advantageous. In order for the Swiss building's design to be as effective if built in other regions, however, further reduction of the operational phase, for example, by solar energy, would be necessary.

Calculations in this study are based on the current electricity mix. We note that homeowners can contract the purchase of "green power", which does not affect the current environmental impacts, although it helps shift the future electricity mix in a "cleaner" direction.

3.2.2. Building life time and Swiss basement removal

An increase of both buildings' lifetimes from 40 to 65 to 90 years reduced their environmental impacts (Fig. 6). According to IMPACT 2002+ GWP of the Swiss building was reduced by 2% and the New Jersey, US building by 3%, when increasing the lifetime from 65 to 90 years.

The scenario without basement performed better than the original Swiss case study building (Fig. 7). According to the IMPACT 2002+ method, the building's life cycle impacts were substantially (>10%) lower in all categories except ODP (3%) and NRE (5%). While both scenarios reduced the environmental impacts, the reductions are not as great as when the electricity mix was changed for the New Jersey, US building.

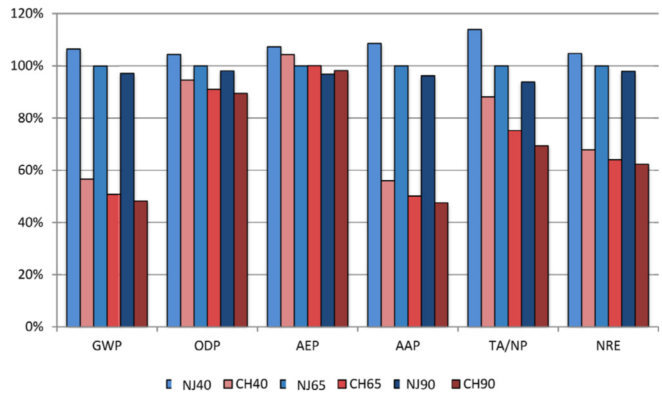

Fig. 6. Normalized life cycle impacts for the two case studies buildings with 40-, 65- and 90-year lifetimes (IMPACT 2002+).

3.3. *Effect of regional construction practices and building rating systems on energy related environmental impacts*

The study compared two typical homes that were designed according to their regional construction practices and rating systems, Minergie P in Switzerland and LEED Silver in the US. Minergie P is a Swiss passive house standard with very high energy efficiency requirements, while LEED Silver has lower energy efficiency requirements, but is the most common LEED standard for single-family homes in New Jersey, US. Complying with regional building practices, the New Jersey, US home has a finished basement and an above ground garage and the Swiss building a below ground unfinished basement and garage. As also typical for the regions the heatable floor area in New Jersey is slightly higher than in Switzerland.

As expected, the Swiss Minergie P building performed better than the New Jersey LEED Silver home regarding the selected energy related environmental impacts. However, since the electricity mix is so important regional building practices, local codes and environmental policies should take the electricity grid into account especially if the reduction of GWP is the objective. Building rating systems take electricity transmission, delivery and production losses into account, but the regional differences in the electricity mix are not considered. In New Jersey, based on the current electricity mix a reduction of the operational energy has priority to reduce NRE and GWP, while in Switzerland the operational phase is less important (Fig. 3 and Table 5). Therefore, for the Swiss building the focus needs to be on the reduction of the energy in the material placement phase, especially if further reduction of GWP is the objective. In addition, when geothermal energy is available, suggestions of Meggers et al. [39] regarding low exergy systems that balance active and passive building components and reduce excessive building shell insulation and fenestration requirements might reduce GWP. If the Swiss building is located in a region with a less favorable electricity grid such as New Jersey, renewable energy such as solar energy could be important to further reduce the non-renewable electricity consumption to operate the heat pump. To lower the operational energy of the New Jersey building, various options need to be considered, ranging from increasing the building shell insulation to further tightening the building or changing the wall system [34] and implementation of renewable energy.

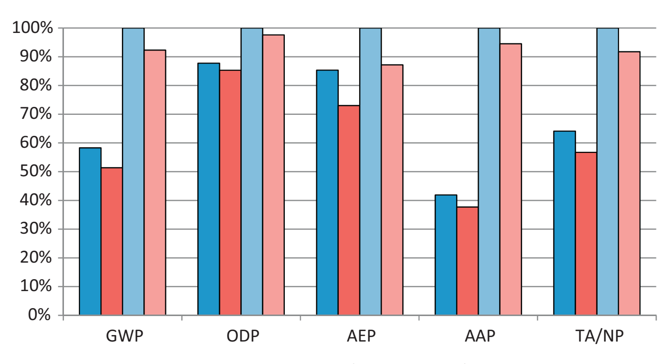

Fig. 7. Normalized life cycle impacts for the Swiss building as is (CH), without a basement (CH-NB), as is consuming electricity from the New Jersey electricity grid (CH in NJ) and without a basement and consuming electricity from the New Jersey electricity grid (CH-NB in NJ) (IMPACT 2002+).

4. Conclusions

The Swiss home was better than the New Jersey, US building regarding all selected impacts. On a heated floor area basis the Swiss building performed better regarding non-renewable energy consumption, Global Warming Potential and acidification. This is mainly a result of both the geothermal heat pump in the Swiss home, which extracts heat from the ground for space heating rather than burning natural gas as in the New Jersey, US home, and the Swiss electricity mix, which predominantly relies on hydro and nuclear power without directly emitting greenhouse gases. There was less of a difference regarding Ozone Layer Depletion Potential and eutrophication, although the Ozone Layer Depletion Potential was generally low for both buildings. The switch of the electricity mix between buildings showed that the electricity sources have a major influence on NRE, GWP and AP impacts, which exceed the effects of longer building life times or the removal of the Swiss basement. Since the electricity mix is so important, regional building practices, local codes and environmental policies should take the electricity grid into account. To reduce GWP in the US, environmental policies in the building sector ideally would focus on regions with a less favorable electricity grid. However, there are no federal regulations addressing these issues and the political process is very decentralized.

For a more complete assessment of the buildings and associated policy choices around building codes, zoning and renewable energy programs other environmental impacts and life cycle costs need to be considered. However, entire building life cycle assessments and standardized data concerning embodied energy are lacking. Therefore, better data are needed to take these issues into account.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.enbuild.2013.09.046.

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