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# Environmental Decision Support for the Construction of a "Green" Mountain Hut

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The construction of a modern mountain hut near the mountains Matterhorn and Dufourspitze in the Swiss Alps is investigated from an environmental point of view. A prospective environmental assessment was performed to minimize the environmental impact already in the planning phase of the new building; construction will start in autumn 2008. An energy balance of the existing hut was made to detect optimization potentials and to predict the necessary energy generating systems of the new building. In addition to energy supply, the environmental impacts of materials and processes were compared and evaluated with the help of Life Cycle Assessment. Although energy use will increase in the new building, mainly due to the installation of a wastewater purification system, total greenhouse gas emissions will decrease.

## Introduction

Mountain huts are often located far from supply infrastructure. Thus, they either need to autonomously provide basic services such as energy generation (*1*) or fuels and other supply goods have to be transported to the hut, e.g., by helicopter. Therefore, a rational use of resources is particularly important for such huts. In the current project, the reconstruction of the Monte-Rosa hut near the famous mountains Matterhorn and Dufourspitze (4634 m) in the Swiss Alps is investigated. The hut is located at about 3000 m above sea level in the proximity of the Gornergrat glacier in the Valais Alps. It is accessible only by foot or helicopter. The existing mountain hut, built in 1894, needs to be replaced.

In a joint project between the Swiss Alpine Club (SAC) and students and professors at ETH Zurich, a new hut with innovative architecture (*2*) and sustainable design was developed. An interdisciplinary research team of civil and mechanical engineers, environmental scientists, and economists planned the technical equipment and conducted prospective financial and environmental assessments. In this paper, only the environmental assessment is discussed. A simulation of the new mountain building, resembling a mountain crystal, is shown in Figure 1. The new building will have a capacity of 120 visitors. Construction is scheduled for autumn 2008.

The energy supply of many isolated systems, such as the current Monte-Rosa hut, relies mainly on oil derivatives and wood because of their flexible use. Therefore, the level of energetic autarky, defined here as the percentage of energy generation from resources already present at the site, e.g., solar power, divided by total energy use, is generally rather low. Mountain huts provide only basic amenities. For instance, inside the current Monte-Rosa hut, there are only dry toilets and no running water. For the new building, the goal was to raise the standard of the sanitary facilities without compromising environmental performance. Therefore, it was planned to install a wastewater purification plant and to base energy supply almost entirely on solar energy. Solar-electric stand-alone systems with a backup based on fossil fuels have already been successfully tested in the European Alps and the Pyrenees (*1*). However, the combination of a high level of energetic autarky (>90%, excluding cooking), constant availability of power, and high quality standards, including modern sanitary facilities and a wastewater purification system, was new and represented a challenge for the planning of the building.

To achieve a high level of ecological sustainability, a life cycle assessment (LCA) was performed and used to support decision-making during the planning phase. While LCA is established as a strong tool for environmental decision support, LCAs of complete buildings are rather difficult to find in the literature (*4–13*), in spite of the substantial growth in green building activities. Notably, there is little published data on the use and disposal phase of buildings. By contrast, LCA studies on the production of building products, such as insulation materials, electronics, etc., can be found rather easily in life cycle inventory databases (*14, 15*). One reason for this lack of data is that materials and processes of environmental concern during the use phase of buildings depend on the specific building operation. Also, it is difficult to obtain reliable long-term data about the durability of building components, in particular at extreme locations, and future conditions and, thus, to model waste scenarios for building materials or to determine reasonable lifetimes for building components or technical equipment.

The present study analyzes the complete life cycle of a mountain hut during its use, construction, and disposal phases. Building-specific inventory data were collected and the environmental impact of the hut was assessed. The aim of the project was to optimize the flows of materials, energy, and water in connection with the whole building life cycle. The project was conducted in the early planning phase, so that environmental improvements could be implemented more flexibly and cost-efficiently.

## Methods

**Energy Flow Analysis of the Operation of the Hut.** The building is used during the mountaineering season from March to September. An energy flow analysis for one season of the existing Monte-Rosa hut was performed in order to estimate the energy demand for the new hut and to detect optimization potentials. Furthermore, this analysis provided input data for modeling the electricity generation system of the new hut. Information about the amounts of various energy carriers used during one season and the necessary helicopter transport was retrieved from the hut keeper. In addition, the electricity demand of technical equipment and the demand profile in the course of the day were measured by installing electric meters with a time resolution of 1 min (Figure 2). One problem encountered was that the electrical system of the old hut was very heterogeneous (various voltages, alternating current (AC) voltage as well as direct current (DC) voltage) because it evolved over many years. A systematic

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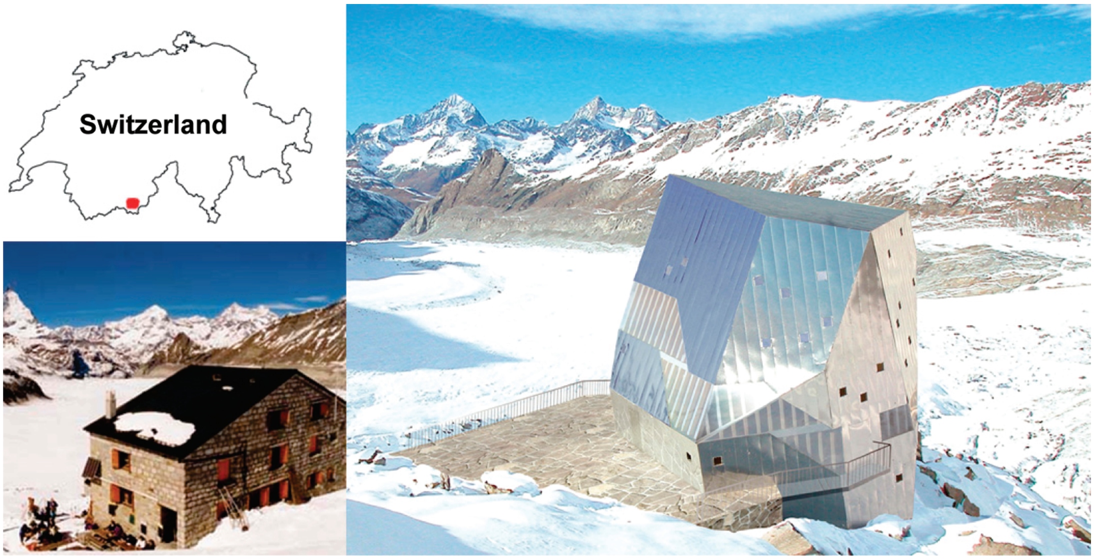



**FIGURE 1. Location of the hut in Switzerland (top left), existing hut (bottom left), and the new hut (right); simulation picture from "Studio Monte Rosa" (*2, 3*).**

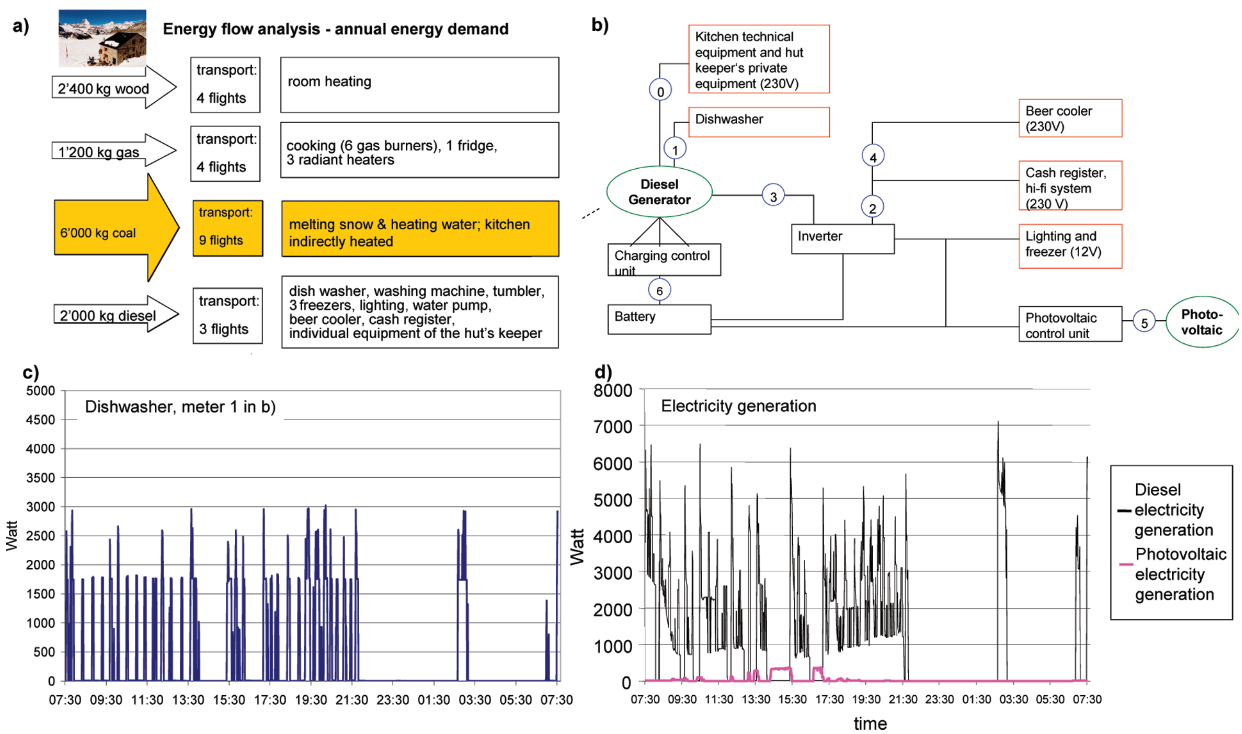



**FIGURE 2. Energy carriers used per season in the existing hut (a), wiring plan (b; the numbers in circles indicate the installation of the seven electric meters, the ovals show the energy generation systems, and the boxes represent the electricity consuming devices), electricity load profile of the dishwasher as an example of a single electricity user (c), and electricity generation profile (d) (measurements from July 30, 2006; 60 overnight guests).**

demand profile was constructed by continuous monitoring from July 30 to August 1, 2006 (Figure 2). The signals of the electric meters were recorded and interpreted with the software LabView. The electric meter types installed in the hut are specified in the Supporting Information (Appendix 12). Electricity-consuming equipment such as a dishwasher, kitchen equipment, cash register, music system, lighting, and refrigeration systems for beer and food were analyzed, and cumulative load and electricity generation curves were generated (Figure 2). The number of visitors staying at the hut was recorded. Extrapolations for the new hut system, including an increased number of guests and additional electrical loads for ventilation and wastewater treatment, were made. Moreover, additional losses from battery storage needed to be taken into account for the new hut, as the photovoltaic electricity is only generated throughout the day, but energy is also needed in the evening (Figure S10). Battery energy losses vary from 5 to 20% (*16*). In this study, losses from batteries and the inverters were assumed to be 15% and 7%, respectively. In addition to new electrical equipment, an increase in energy efficiency of the present equipment was taken into account. Furthermore, a gradation was made from electricity consumption from equipment that is completely dependent on the number of guests, such as operation of the dishwasher, to the use of equipment independent of the number of visitors, such as the huts keeper's music system. Moreover, some consumers such as ventilation and lighting only depend to a certain degree on the number of visitors, because, for instance, the light in the restaurant will be switched on even if there are only very few guests, but less lights will be used in the sleeping rooms, since with few guests only a fraction of them will be used. In addition, there are anticyclic electricity users. For example, the washing machine is more often used in off-peak times, because the guests are not allowed to use the machine and the hut keeper has more time for doing the laundry. To model the entire system, it was assumed that there is a base consumption plus a variable component that depends on the number of guests.

The meteorological simulation tool *Meteonorm version 5.1* (*17*) was used to quantify electricity production from the new photovoltaic system, assuming constant panel inclination of 66° (*18*) and accounting for snow reflections. Hot water production from the solar panels was modeled as well. *Meteonorm* included weather data of the past 20 years as well as data about total solar irradiation. All variables of the building's services are shown in the Supporting Information (Appendix 11). By contrasting the energy generation and the energy demand, an energy budget, including surplus energy production and operational times of the fossil backup system, was estimated. The energy budget helped determine the autarky level of the system and identify uses for the surplus electricity generated. Data for the heat requirements of the hut, including warm water, were taken from the engineers in charge of the technical equipment (*18*).

**Environmental Assessment of the Construction, Use, and Disposal Phases.** With the help of Life Cycle Assessment (LCA), the environmental impacts of construction alternatives were compared and evaluated. Data for the building materials and technical equipment came from the architect's plans (*2*) and tendering drafts for the foundation (*19*) and timber construction (*20*). The LCA was performed in the planning phase; however, only the final plans and some of the most important planning alternatives, e.g., with regard to the building skin, are discussed. The software tool *SimaPro 7.0* (*21*), which included inventory data sets of the *ecoinvent 1.3* (*22*) database, was applied to identify and thus avoid assemblies and materials of ecological concern. The functional unit was the construction, use, and deconstruction of the mountain hut, assuming a lifetime of 50 years.

In the impact assessment the indicators cumulative energy demand (CED) and climate change factors of the IPCC 2001 (*23*) with a time frame of 100 years were used, as energy-related impacts were of primary interest in the project. In addition, Eco-Indicator 99 (H) (*24*) was applied to confirm the validity of the results (see Supporting Information, Figure S12).

The Monte-Rosa hut will be a timber construction based on a steel foundation. The LCA investigates the following subassemblies: foundation, outside walls, inside walls, roof, floor and ceilings, building service instruments and materials, staircase, terrace, and furniture. Everything will be preassembled and transported to the building site by helicopter. Some wood-construction components will be digitally fabricated (*3*), which allows for simplified glueless assembly. For the building skin, three different skin types with equal insulation properties were considered: vacuum insulated panels (VIP), insulated glass panes, and a conventional insulated building skin of 30 cm thickness using mineral wool. Material replacements and abrasions over the use phase were not taken into account. For detailed information on the composition of the different building skin types and all building components see the Supporting Information (Tables S6−S8).

The technical equipment included batteries for storing the electricity produced by photovoltaic panels, the tanks for storing water, wastewater treatment plant infrastructure, the combined heat and power unit, electronics, lamps, and sanitary equipment. For details, see the Supporting Information (Appendix 6).

The waste scenario was based on 80% recycling and 20% landfilling of steel and aluminum, and 100% burning of wood. With regard to the steel recycling process, it was assumed that cast iron could be re-extracted in a conditioning process by adding scrap iron to the used steel (*25*). The batteries were assumed to be recycled as well. Inventory data to generate the battery recycling process were obtained from a specialized enterprise (*25*), while the composition of the used lead batteries was based on manufacturer's information (*16*). The battery lifespan was assumed to be 17 years. Thus, during the time period of 50 years, all batteries were assumed to be renewed twice. With regard to all recycling processes, credits were given for the avoided primary products as specified above. The silicate hydrate product, used as heat storage material in the glass facade, was assumed to be thermally treated as hazardous waste. Inert materials were assumed to be landfilled. All assumptions are documented in more detail in the Supporting Information (Appendices 1−9).

The use-phase scenario (Supporting Information, Appendix 10) comprises the energy supply and transport of food and drinks. Energy use in the LCA model is projected based on the energy use and generation forecast. The hut will use electricity from 84 $m^2$ of photovoltaic cells and hot water will be produced by 56 $m^2$ of solar flat plate collectors. A combined heat and power unit, based on natural gas, will serve as backup system. Cooking will be done with natural gas.

During the use phase, helicopter flights are needed to transport food, drinks, and energy carriers to the hut. Guests' transport was not included. Information about the kerosene demand of the helicopter and the flight time was retrieved from the local helicopter shuttle (*27*).

Water availability was estimated by using measurement data over the past 30 years from the Laboratory of Hydraulics, Hydrology and Glaciology at ETH Zurich (VAW) (see Supporting Information, Figure S14). Various water-use scenarios were considered to minimize freshwater use and wastewater amounts.

## Results

**Energy Flow Analysis of the Existing Hut.** The energy balance of the existing hut indicated that the most energy-using activities are cooking, melting snow, heating water, and providing electricity, which together amount to about 80% of the raw energy demand (Figure 2a).

The average temperature at the site of the Monte-Rosa hut is below the freezing point. Despite the extreme weather conditions at the location of the hut, less than 10% of the energy demand is needed for direct heating, because in the existing hut only the restaurant is heated, with waste heat from cooking. In the new hut, heating with fossil fuels will not be necessary during the tourist season because of the well-insulated building skin, use of solar energy, and waste heat recovery from the ventilation system. However, during the winter the hut may have to be kept at 5 °C because of the technical building equipment.

Water melting and heating is responsible for the largest fraction of fuel use in the current hut, amounting to 6000 kg of coal annually (Figure 2). This unexpectedly large resource use is expected to decrease with the new hut's more sophisticated water systems (see Water Availability and Wastewater Treatment).

Another relevant fuel use was the generator, which consumed 2000 kg of diesel per year to provide the hut with electricity. The existing small photovoltaic installation did

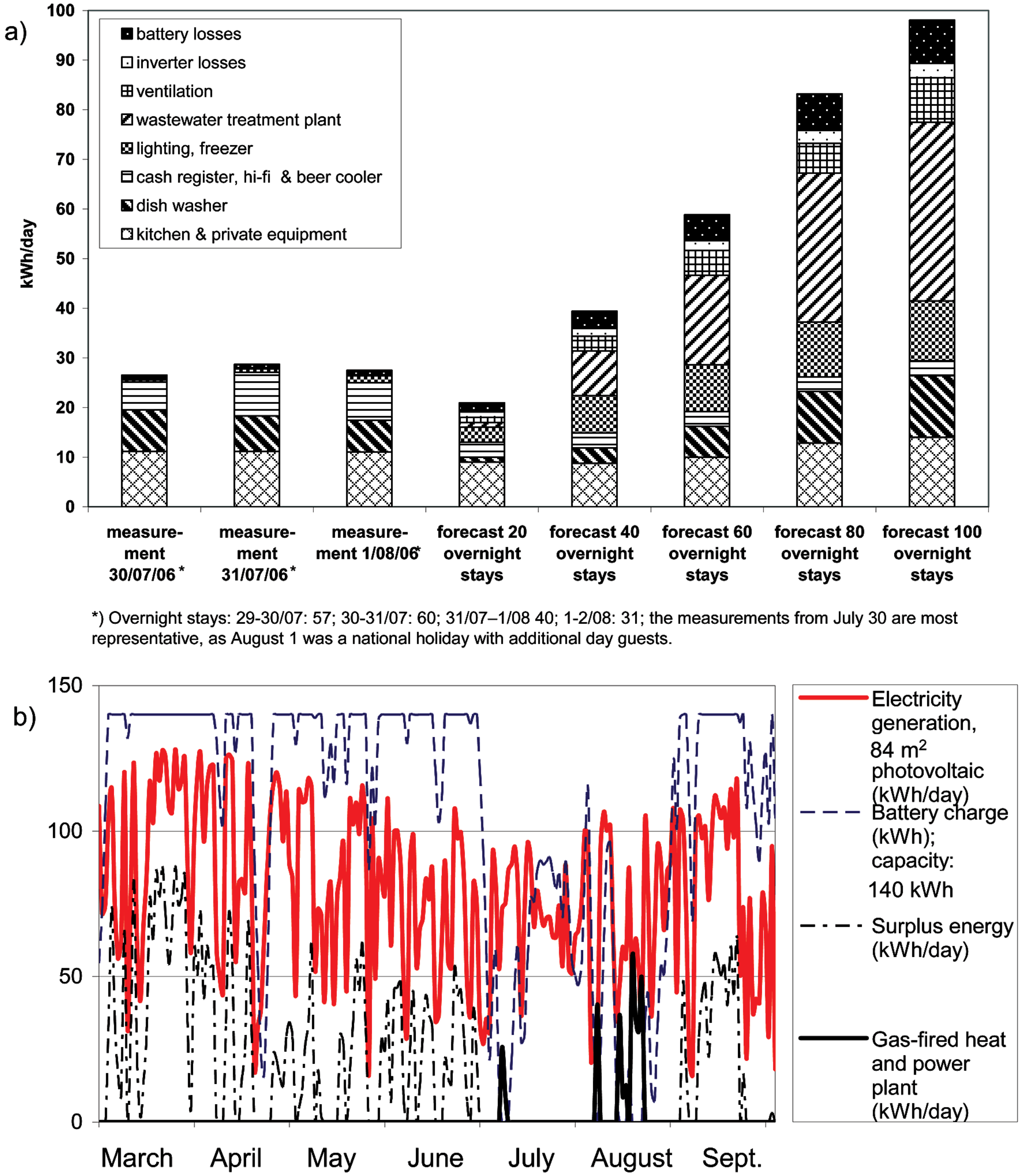


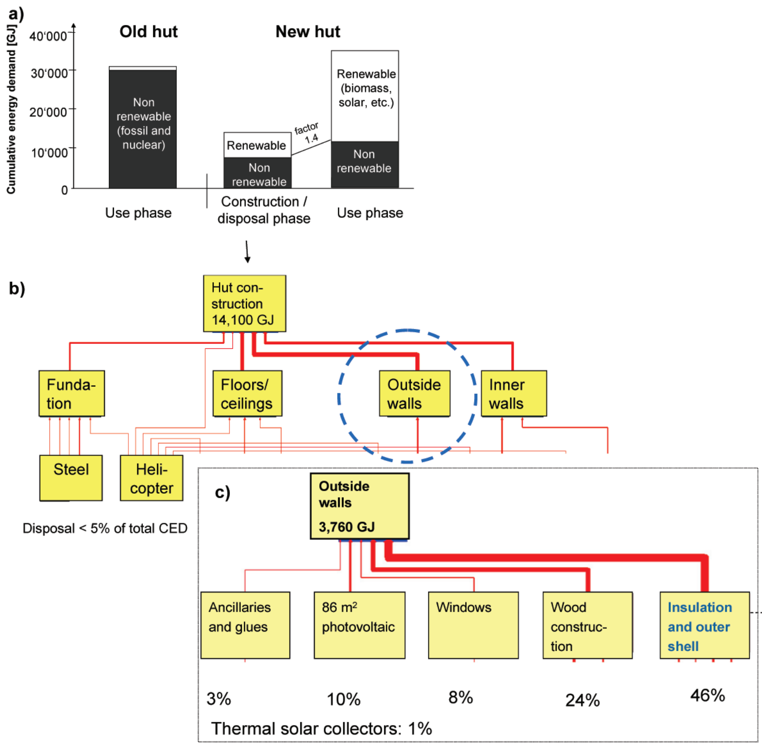

**FIGURE 3. Daily electricity demand measured at the old hut (3 bars on the left) and extrapolations for the new building (5 bars on the right), as a function of guest number (a) and simulation of energy generation (photovoltaic 66° incline) with Meteonorm (*17*), battery storage, use of the backup combined heat-and-power plant and surplus energy (b). Energy consumption was modeled as a function of variable overnight stays and electricity consumption (see Tables S29−S31).**

not contribute significantly to the hut energy needs due to nonoptimal installation (Figure 2d).

The load profile measurements identified the dishwasher as a main consumer, as well as the accumulated hut keeper's private equipment. Figure 2 shows the aggregated electricity generation profile as well as the load profile measurements of the dishwasher (see Supporting Information for all other load profiles). Electricity is used throughout the day, with a small break after lunch. At night there is only one peak when the first mountaineers get up to climb mountain Dufourspitze. In Appendix 13 of the Supporting Information the technical equipment of the existing hut with the related daily energy consumption based on the measurements is listed.

**Energy Flow Analysis of the New Hut.** The measurements performed at the existing hut served as a basis to estimate the electricity demand of the new building. To keep electricity demand low, much attention was paid to the energy efficiency of the technical equipment. For instance, machines with high or unnecessary electricity consumption, such as the clothes dryer and electric beer cooler, will not be used in the new building. Instead, there will be a natural cooling system for drinks and a drying room for the laundry. However, in order to run a large restaurant and to provide the hut keeper with a minimum level of comfort, electrical equipment is necessary. Specifications of the technical equipment and the assumptions made for the extrapolation are documented in the Supporting Information (Appendices 14 and 16).

Figure 3a shows various electricity consumption scenarios with varying numbers of guests. If the hut is fully booked with 120 guests, the energy demand increases to about 100 kWh per day. The wastewater treatment plant accounts for the biggest fraction of electricity use, as it uses energy for




| Skin types | Conventionally insulated skin per m² | Vacuum insulated panels per m² | Glass panels with heat storage material per m² |
|---|---|---|---|
| Schematic build-up | *700 m² | | |
| Weight (kg) | 56 | 40 | 90 |
| CED (MJ) | 2340 | 2630 | 2910 |
| - production | 2470 | 3460 | 2260 |
| - disposal | -133 | -832 | 651 |
| GWP ($CO_2$-eq.) | 51 | 146 | 191 |
| - production | 11 | 187 | 121 |
| - disposal | 40 | -41 | 70 |

**FIGURE 4. Cumulative Energy Demand of the construction/deconstruction phase and use phase over a time frame of 50 years (a) and process tree of the construction phase (b). Thickness of the connecting lines reflects the relative impact of processes. The inner window (c) shows the subtree for the outside walls and the table various alternatives for the facade. In the process tree, the insulation material was assumed to be mineral wool and the outer shell was assumed to be aluminium (see Supporting Information for details).**

aeration, as well as for the agitator and water pump. Despite this system's energy use, it represents a great improvement on the current practice of directly releasing untreated wastewater.

Figure 3b shows that a high level of autarky can be achieved if the scenario assumptions hold. After longer periods of good weather, when the batteries are charged, surplus energy is generated. On average, electricity demand should be kept below 80 kWh, assuming a battery storage of 140 kWh. On peak days, with more than 80 guests, electricity consumption may be higher. However, according to the hut keeper, many guests favor clear, sunny weather. Therefore, large guest numbers are expected to correlate with high solar irradiation levels. The resulting increased photovoltaic generation helps mitigate the increased electricity demand. On the other hand, it is possible that, given the widespread publicity this new mountain hut has already obtained (*28, 29*), the SAC-projected 25% increase in guest stays will underestimate the true number, causing a larger energy demand.

**Life Cycle Assessment.** The life cycle assessment of the new mountain hut showed that the choice of materials is important to lower fossil Cumulative Energy Demand (CED) and emissions contributing to climate change. The fossil CED of a product represents the direct and indirect fossil energy use (i.e., demand of hard coal, lignite, peat, natural gas, and crude oil) throughout the life cycle, including the energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials (*31–33*). The new hut will be built mainly with wood. Wood is a renewable material, and thus, it is $CO_2$ neutral to a large extent (except for transport and processing) (*14*).

Looking at all components and assemblies of the final architectural plans, the facade has major environmental impact in the construction and disposal phases, due to the large amount of surface cladding needed (Figure 4). The analysis of the different building skin types showed that the conventional skin is the most advantageous solution using the CED and global warming potential indicators. The building skin of glass would cause the highest $CO_2$-equivalent emissions and the highest cumulative energy demand per square meter. Furthermore, the mass is twice as large as the mass of the other facade alternatives. The material mass is important because a significant portion of the overall environmental impact comes from helicopter transport. Helicopter flights produce about 30% of the global warming potential emissions during the construction and deconstruction phases. Such transports should therefore be scaled down to a minimum to reduce environmental impact and costs. As for the VIP, environmental impact may be minimized by reducing the thickness of the mantle. The VIP skin would also score better if it were recycled into higher-value products such as chromium steel (in this paper recycling into low-grade steel was assumed). However, if a cutoff allocation approach were used, assuming that the steel would not be recycled in the disposal phase, VIP would be on par with the glass facade (Figure 4).

The batteries for photovoltaic cells are needed to store energy, because two-thirds of the electricity is used during night hours (see Figure S10) and periods of bad weather. The environmental impact of the battery system is considerable due to carcinogenic emissions in the production and recycling stages (Figure S12).

Over 70% of the cumulative energy demand occurs during the use phase. During both the construction and use phases a large fraction of the energy used originates from renewable sources, due to the use of wood as main building material and from the utilization of solar energy.

$CO_2$-equivalent emissions of the hut operation per overnight stay will be reduced to one-third of the current value in the new building (Figure 5). This reduction in $CO_2$-emissions is due to the avoided amounts of coal and diesel for electricity production and snow melting (Figure 2). The

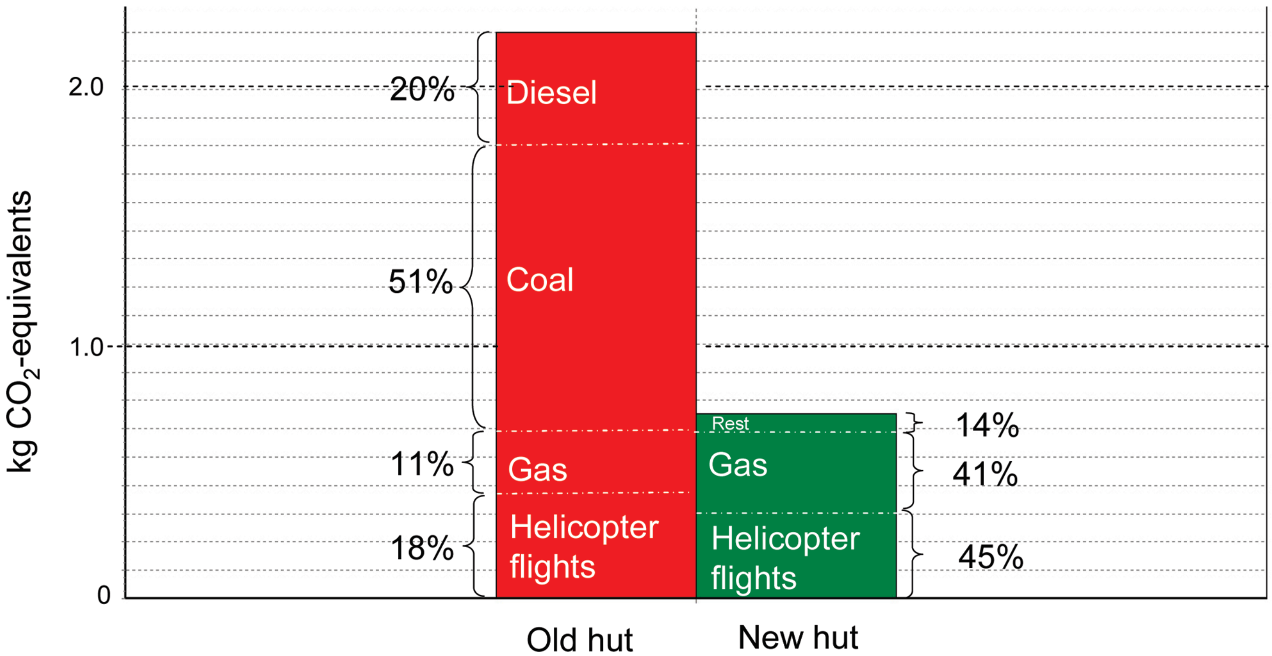



**FIGURE 5. Comparison of the $CO_2$-equivalent emissions per overnight stay for the old and the new hut (only operation, without hut construction and disposal).**

remaining $CO_2$-equivalents mainly result from the helicopter flights for transporting food and from the cooking gas. The combined heating and power unit seems to be less relevant, since it is only used in exceptional cases and possibly during the winter, when the solar panels do not produce enough heat to maintain a minimum temperature of 5 °C in the building.

To reduce fossil $CO_2$-emissions, the use of biogas was considered. However, the energy density of biogas is lower than that of liquid natural gas. Therefore, more helicopter transports would be necessary for biogas, which would offset part of the $CO_2$ reductions. Another solution would be to use the energy surplus of the photovoltaic system (Figure 3) in electric induction cookers (efficiency of 85%). During the season, the photovoltaic system is expected to produce about 4000 kWh surplus electricity. This is equivalent to the energy content of 480 kg propane gas, assuming a heating value of 12.9 kWh per kg and an efficiency of 55% for gas cookers (*30*). Solar cooking systems could be an option as well. However, traditional solar boxes and reflector cookers alone are not able to cover the energy demand for cooking in a practicable manner. New developments in solar cooking systems may change the situation in the future. Thus, the global warming emissions in Figure 5 may be decreased even further. The helicopter flights for transporting food may be reduced as well, e.g., by avoiding products with a high packaging or waste amount, especially glass bottled drinks.

**Energy Management System.** An energy management system and remote monitoring of energy use and production is planned to help maintain the high autarky level and to avoid using the backup system based on fossil fuels. With this system, weather forecasts will serve to forecast energy production and to schedule energy demand accordingly. For instance, energy consumers such as the washing machine or wastewater treatment plant may be shut down temporarily, based on a defined hierarchy of services (*18*).

**Water Availability and Wastewater Treatment.** Water availability at the site of the new building is sufficient to cover the demand, but it varies seasonally and yearly (Figure S11). For times of low water availability, to avoid energy-intensive snow-melting in the hut, insulated tanks with a capacity of 150 $m^3$ shall store the water over the year (*18*). Due to UV treatment only water which serves for drinking purposes needs to be boiled. Also, water demand is reduced by recycling about 100 $m^3$ of toilet water every year, using a membrane biological reactor for treatment (*18*). A wastewater treatment plant of the same type already operates successfully at a similar elevation (*34*). The drawback of wastewater treatment is high energy use (see Figure 3). At peak load, the wastewater treatment plant needs 36.5 kWh per day (*18*).

## Discussion

Compared to other mountain huts, the new Monte Rosa hut will offer high accommodation standards for the mountaineers, which leads to an increased energy demand. However, more than 60% of the cumulative energy demand stems from renewable resources. This is a very high fraction compared to the old hut (Figure 4a) and other similar huts in the Swiss Alps, highlighting the importance of a careful choice of energy supply sources and building materials. With regard to the nonrenewable cumulative energy demand, the use phase of the hut was only 40% more important than the construction/disposal phases, considering a time span of 50 years. This is clearly different from other studies of buildings, in which the use phase dominated the construction and disposal phases (e.g., *5, 10, 11, 13*). Recent work (*7*) confirms the emerging importance of construction and deconstruction compared to the use phase in case of passive houses, which, as a consequence of a better building design, have more efficient operation.

In spite of the increase in electricity demand, the $CO_2$-equivalent emissions per overnight stay in the new building will be only one-third of the emissions of the present hut. This decrease in $CO_2$ emissions is achieved, first, by primarily using renewable energy sources and building materials, second, by a well-insulated building and energy-efficient equipment, and, third, by avoiding snow melting through optimized water management. Moreover, a modern wastewater purification system reduces the impact of water emissions to the environment. Thus, the new Monte Rosa hut may provide a new benchmark for mountain huts, with high environmental performance, modern architecture, and high-quality standards for the guests.

However, the hut keeper's and especially the guests' behavior is crucial for the overall environmental impact (*35*). For instance, many visitors travel over large distances to the hut, some even taking helicopters for the final ascent. Such journeys clearly dominate the energy balance of a mountain trip. The good environmental performance of the hut is nonetheless important, because the hut has a high visibility and will therefore be recognized as a good example for energy efficiency. As such, it hopefully serves as a model for many other buildings in the valley, where energetic optimizations are far easier to implement than at such an extreme location as Monte Rosa.

Further improvement potentials include the implementation of cooking systems that do not run on fossil fuels. Such systems are currently under development. Also, the energy supply system could be enhanced by a wind power plant. Solar power is especially effective at the site of Monte Rosa, because of high yield factors due to the height and snow reflection. Further, the number of guests staying at the hut is believed to correlate with nice weather. However, a large battery storage system is necessary to meet the nighttime energy demand and for periods of bad weather. These batteries cause considerable environmental impact. With a wind turbine, it may be possible to cut down the storage capacity of the batteries, as wind power production is expected to be complementary to solar electricity production. Finally, it is currently examined whether the building should not be heated at all during the winter time, when no guests come to the hut. Although heating accounts only for a small use of fossil fuel, it may thus be possible to run almost completely on solar energy for heat production.

The current study is an example for prospective assessment of environmental impacts and for environmental decision making in the early design phases. This enabled an easy implementation of environmental improvements, which were identified in an iterative procedure in collaboration with an interdisciplinary team. Thus optimizations could be implemented more efficiently.

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## Supporting Information Available

Details on the material composition of the new building, measurement devices, technical equipment, energy use forecasts, water availability, and additional LCA results. This material is available free of charge via the Internet at http://pubs.acs.org.

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