RoofKIT - Circular Construction and Solar Energy Use in Practice at the Solar Decathlon Europe 21/22

To cite this article: A Wagner *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1078** 012058

RoofKIT - Circular Construction and Solar Energy Use in Practice at the Solar Decathlon Europe 21/22

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Abstract. The contribution of the RoofKIT team to the SDE 21/22 competition is the extension for an existing café in Wuppertal, Germany, to create new functions and living space for the building with simultaneous energetic upgrading. The energy concept targets all renewable resources available on and in the building for energy supply: mainly solar energy which is used via PVT collectors, as well as waste heat from ventilation and grey water which is recovered for pre-heating. As part of the competition, a demonstration unit will be built representing a small cut-out of the extension. An integral building and energy concept combines physical properties of the building with adapted building services technologies to achieve maximum indoor comfort – particularly considering possible overheating of the lightweight construction during summer – and minimum CO_2 emissions. The latter extends to the whole lifecycle of the building unit and one of the major goals of the project is to realize an almost completely mono-fraction and circular building construction as a contribution to the urban mining concept.

Keywords: Circular building construction, urban mining, PVT collectors, passive cooling

1. The RoofKIT project

In view of the advancing climate change as well as the shrinking natural material resources, a fundamental rethinking in building industry is necessary. The further development and conversion of the existing building stock, a circular design and construction using the urban mine, the use of materials that are harmless to health and the environment as well as a CO_2-neutral energy supply are core tasks of the construction sector. The student team RoofKIT of the Karlsruhe Institute of Technology (KIT) is accepting this challenge by designing a piece of future architecture for the Solar Decathlon Europe 21/22 in Wuppertal.

1.1. Building design

Seeking for innovative strategies for the densification of the existing European city, the RoofKIT team has chosen to work on an extension of the Café ADA in the Mirker district of Wuppertal, Germany. RoofKIT not only creates new living space, but takes the historic building and its use as an international meeting place for tango dancers as the initial point for an integrated solar-based design concept.

The exterior of the existing building remains largely unchanged to remain as a point of identification in the neighborhood, with an energetic upgrade of the building envelope. The newly designed ballroom will be moved up one floor. Through its form and materiality, it spatially forms a transition between the existing building and the new structure. The space thus gained by the former dance hall will be converted into accommodations for international artists and other temporary residents (figure 1).

The additional residential units on top of the new ballroom will be manufactured as prefabricated wooden modules. This allows for quick and simplified assembly on the construction site. The elevation presents a concept of shared spaces to renegotiate the available individual as well as the commonly used space. Thus, RoofKIT aims to address the needs of residents in different living situations – among them students, families and seniors – and shall help to create a social togetherness as a community.

Figure 1: Visualization of the overall building - Café ADA with addition of new dance hall and housing.

1.2. Building services and energy concept

RoofKIT follows a holistic approach in which the energy concept is an integral and visible part of the architectural design from the very beginning: a synthesis of passive measures (e.g. use of solar energy and daylight, natural ventilation, passive cooling) for high indoor environmental quality and innovative solutions for energy supply, yielding carbon neutrality over the year. The measures extend to the improvement of the urban microclimate and outdoor comfort around the building by known approaches as unsealed green surfaces, plants and shading.

High-quality thermal insulation and central ventilation heat recovery minimize heating requirements, and the use of solar energy and daylight also contributes to the building's low energy consumption. In summer, a passive cooling strategy keeps interior temperatures within the desired comfort range. Clay boards are integrated into the lightweight construction of the extension in order to dampen the dynamics of the interior temperature with thermal mass. The thermal mass in both parts of the building is discharged by natural ventilation during nights. In the residential part of the extension, an atrium improves the night ventilation by the buoyancy effect.

The building's energy supply is based on solar PVT collectors that simultaneously provide electricity and heat for a heat pump. Energy management maximizes the self-consumption of solar energy and the building's grid serviceability by optimizing solar yield, electricity demand, and charging / discharging of batteries (building and e-bikes) and a thermal buffer storage. Heat recovery from a central grey water heat exchanger further contributes to the building's high energy efficiency. The conversion of biowaste into biogas for cooking is also taken into account to extend the idea of circular economy to technical processes in the building. Together with the design features for energy efficiency, it is possible to cover the annual energy demand with solar energy and heat recovery (figure 2).

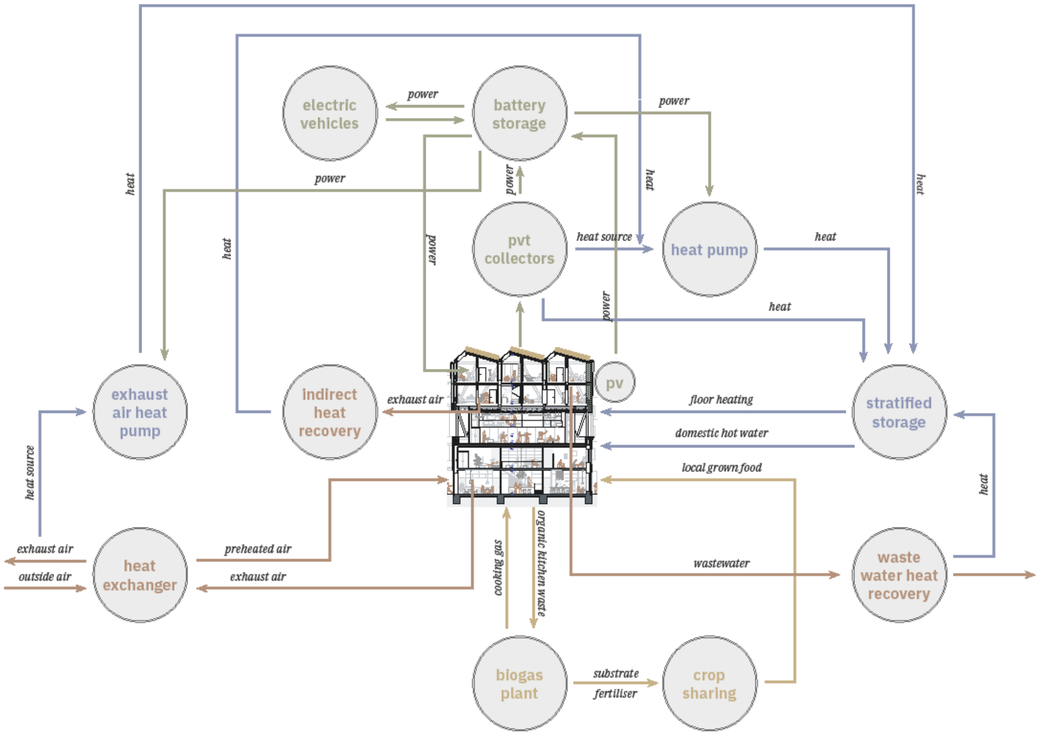

Figure 2: Schematic representation of the energy concept for the RoofKIT project.

2. The realized building unit (House Demonstration Unit - HDU)

For the competition in Wuppertal, a residential unit from the elevation is simplified and "cut out" as a demonstrator (figure 3). It consists of four prefabricated modules with a central core that bundles all technical installations as well as the kitchen and bathrooms. This leaves almost the entire open floor area of the unit for living, working and sleeping. To demonstrate the elevation, the building unit is placed on a scaffolding, and the area underneath the building is used additionally for visitor access during the competition, in allusion to the dance hall, but also for technical equipment that would otherwise be found in technical rooms in the existing building.

The energy supply concept explained above, including energy management, is also adopted but scaled down to requirements. The inverter, battery and a source-side storage tank for the heat pump are installed underneath the unit as described above. For ventilation in winter, oscillating decentralized ventilation systems with heat recovery are integrated into the façade in deviation from the overall design. Night ventilation for passive cooling is provided via the windows and skylights in the bathroom area.

2.1. Building envelope of the HDU

Wood from various recycled stages is used for the load-bearing structure of the HDU as well as for sheathing to further reduce the global warming potential of the building also through stored CO_2. In addition, the reuse of all materials and components is ensured through mono-fraction construction without non-detachable connections in order to avoid final combustion or landfilling as far as possible.

The thermal insulation of the entire building envelope is realized with a natural product based on dead water plants, which is processed without additives.
Another special feature are the windows – so-called stock windows, i.e. windows from or for other building projects, are used for the HDU. The primary selection criterion is adequate thermal insulation – all windows are triple-glazed. Different window sizes are used as a design feature.

Figure 4 shows a section through the building envelope, which shows the sequence of layers in the structure to ensure moisture protection and wind tightness. Since the HDU is elevated and thus connects to outside air on all six sides, the floor area must also meet the high requirements for thermal insulation – unlike in the case of an addition. All U-values of the building unit are close to passive house standard.

Figure 3: View of the realized house demonstration unit (HDU).

3. Thermal comfort in summer

To ensure a comfortable indoor climate in the summer months, a passive cooling concept is implemented in the HDU. A particular challenge here is the introduction of thermal storage mass into the lightweight construction. For this purpose, clay boards are integrated into the exterior walls (here with additional loam rendering) as well as in two layers in the floor - above the underfloor heating (see figure 4). In addition to the thermal storage effect, the moisture buffering effect of the clay is a further benefit to profit from. Another important component for passive cooling is solar shading, which is realized at the HDU with external textile screens made of recycled materials.

For effectively discharging the thermal mass by night ventilation, reasonable ventilation rates have to be achieved. Therefore, a night ventilation concept with the façade windows and skylights in the bathroom area is implemented, thus utilizing the buoyancy effect which guarantees higher air change rates. Dynamic thermal simulations with a one-zone model [1] show that the proposed solution achieves indoor temperatures that are within the desired range of the adaptive comfort model according to DIN EN 16798 (categories 1 and 2) for 90% of the time (see figure 5). The skylines are operated automatically through the energy management system which also involves the occupants into the decision process. The occupants receive notifications from the installed interface about when to open the façade windows to improve the effectiveness of night ventilation.

4. Solar harvesting

The HDU's roof (without the roof of the patio) is covered with 18 solar modules in total. Simulations showed that 12 PVT collectors are enough to serve as a heat source for the heat pump. A buffer storage of 1.000 l separates the collector circuit and the heat pump's evaporator circuit and helps to adapt the operation of the collectors to periods with sunshine and ambient temperatures above 0°C to avoid icing around the fluid pipes.

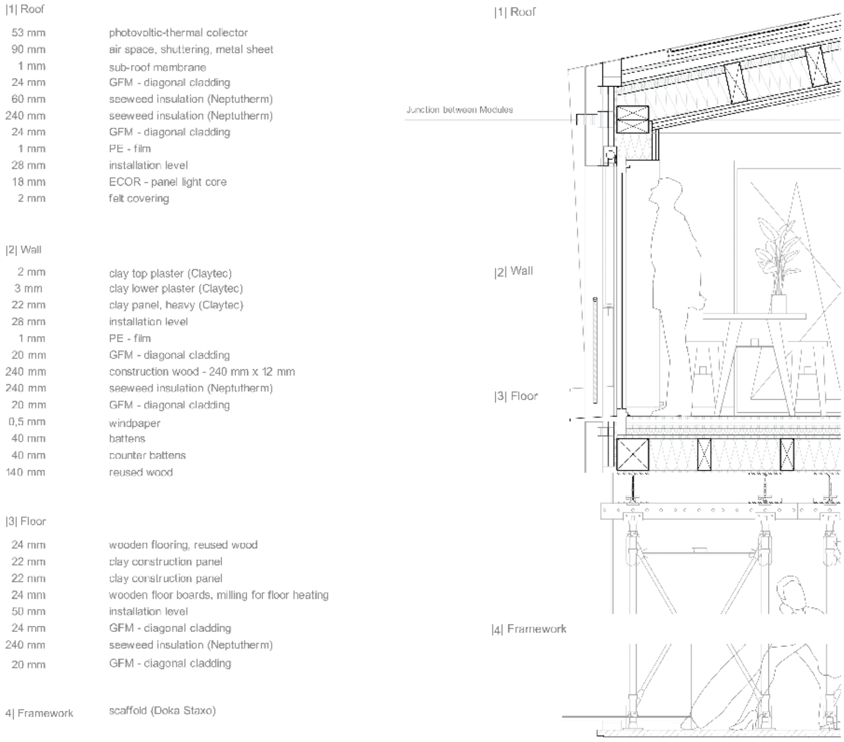

Figure 4: Section through exterior wall, roof and floor of building unit (HDU).

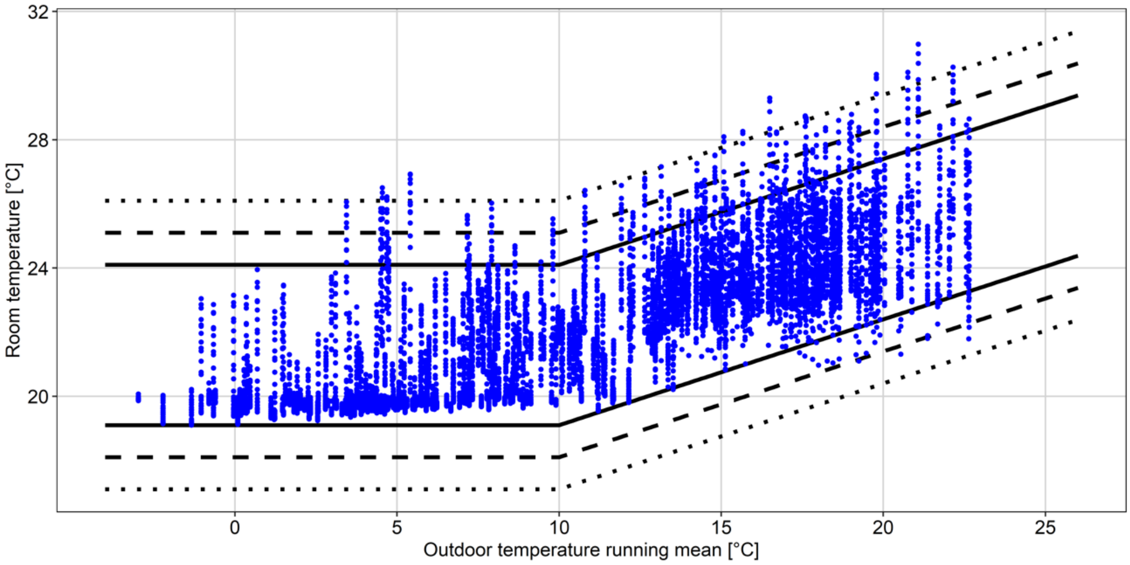

Figure 5: Operative temperatures as a function of the running mean of the outdoor temperature, together with the comfort band of the adaptive comfort model according to DIN EN 16798.

In addition to the 12 PVT-collectors, 6 more PV modules are installed (5.4 kW_p in total) to achieve a homogeneous roof cover and to provide enough electricity for the later operation of the HDU as a guest house at KIT in Karlsruhe (heat pump, household electricity, mobility) on an annual basis. The PV modules have a rusty brown color which is identical to the roof color – integrating the solar roof perfectly into the architectural design of the building. With an innovative coating technique, the PV modules show a comparably high efficiency and PVT technology helps to increase PV output as the solar cells are cooled by the brine circuit.

An inverter serves for connecting to the (AC) SDE campus grid and the distribution network of the city, as well as to the battery (DC) and the low voltage (AC) network of the HDU at the same time. Therefore, no second inverter is necessary and the overall efficiency of the system is improved. Electric energy can be stored locally in a battery with a capacity of 5 kWh and additionally in the battery of an e-bike. The operation of the inverter and battery charge is optimized through the installed energy management system.

Simulations show that the HDU generates 95% of the electricity that it consumes on an annual basis, which means that carbon neutrality is almost reached. The average self-consumption is 83%, meaning that this amount of the generated energy is consumed directly, and the rest must be taken from the grid.

5. **Minimizing the carbon footprint of the building**

5.1. General approach

One of the major objectives of RoofKIT is to minimize its carbon footprint by emissions and other environmental impact throughout the whole lifecycle. This can be achieved through an urban mining approach which means reusing materials and (building) components as well as integrating recyclable natural and cultivated materials (see sections below). Furthermore, RoofKIT's concept of prefabricated modules is a significant step towards transforming urban mining into an industrialized building process.

5.2. Natural, mono-fraction and recycled materials

RoofKIT uses a large amount of wood-based materials from different reuse and recycling stages that have a positive effect on the Global Warming Potential due to the carbon bond of wood during growth. Furthermore, thermal utilization of wooden materials at the end of their life cycle will be avoided (even if a high efficiency is assumed according to EU standards). Instead, RoofKIT focuses on reuse, recycling and down-cycling as long as possible, as it helps preserving forests and gives them time to recover. Further materials, likewise taken from the natural cycle, are insulation materials based on dead water plants (building envelope) and cork (piping), both causing only low emissions as they are extracted from nature and hardly processed. For the ceiling, fiberboards made of biological waste materials hold a covering of pure sheep felt without synthetic additives.

RoofKIT also focuses on keeping materials in the most natural way possible in order to fulfill the claim to only use mono-fraction materials. Again, the insulation materials serve as a good example: the dead water plants are shredded by the movement of the sea and are only mechanically processed for the use as insulation material. The same is figuratively true for the sheep felt. Cork is peeled from the cork oak, then ground into granules and treated with superheated steam which leads to a natural expansion of the granules. Furthermore, the cohesion between the granules is accomplished by the trees' own resin, which makes it possible to produce different forms for insulation.

In addition, a variety of materials from secondary streams are applied in RoofKIT to avoid the waste of resources. Examples are products from waste glass, old yogurt cups or waste wood. The roof sealing is made of recycled copper material.

5.3. Detachable constructions and urban mining

An important prerequisite for reuse of building materials and components is its detachability. In RoofKIT, a pure solid timber construction without the use of adhesives is realized with static wall stiffeners in massive diagonal formwork technology. All wooden connections are executed with CNC technology and without the use of screws or nails. Dry seals are used instead of wet seals with the help of clamped profiles and no synthetic-mineral floor coverings are applied, thus avoiding adhesives, fillers and joints. A floating floor construction was chosen without otherwise common adhesives or bonding techniques which is also true for vapor and moisture barriers which are loosely overlapped or clamped. The clay boards to increase thermal mass were bolted in the walls and floor.

Strong emphasis is laid on using materials from the urban mine and to understand this as a design principle. For example, by using stock windows (see section 2.1) there is no need to custom-make new windows for the building unit at all. The same applies to the complete fittings of the WC and shower which originate from exhibition returns, for the used entrance door, for the primary wood beams of the truss construction, a used industrial staircase including railings, the latter being taken back after the competition, and the scaffolding. By doing so, RoofKIT acknowledges the value of second-hand items and the economic efficiency of urban mining materials.

5.4. Transportation

RoofKIT also tries to reduce carbon dioxide emissions caused by transportation by using as many local and regional materials as possible. The entire demonstration unit is prefabricated in a factory in Vorarlberg, Austria. There, only wood (silver fir) from certified, sustainable forestry of the region is used, so that transportation routes remain at a minimum level. The clay boards and the PVT-collectors are delivered by companies also located in Austria. Thus, almost all the used building materials and fixtures originate from Germany or neighbouring countries.

5.5. Evaluation of environmental performance of the HDU

The global warming potential for the HDU was analyzed according to EN 15978. Related values for for the structural elements were taken from the Urban Mining Index tool [2] (using data from the German database “Ökobaudat” Version: 2021-II from 25.06.2021 [3]) and the values for the technical components from the eLCA tool (Version 0.9.7) [4] on the basis of a mass calculation and a component list. The carbon footprint was calculated over a standardized life cycle of 50 years for the HDU with a reference net floor area of 54 m^2. The balancing includes the production of the building materials and the technical equipment, the usage phase including the operation and maintenance of the building, as well as the disposal. Appliances and furniture were not included. Values for the life span of building components and construction were taken from the German industry standard DIN 276, values for technical installations and technical systems from VDI 2067.

During the manufacturing phase (phases A1-A3, EN 15978), emissions are mostly caused by services systems, like the heating system with the PVT collectors, battery storage, decentralized ventilation systems, plumbing and general installation, with 40,7 kg CO_2e. Sustainable building construction with a high fraction of natural materials like wood or seaweed insulation as well as a lot of secondary raw materials like glass ceramics, storage windows or rented materials like the scaffold towers, reduces the global warming potential in this phase significantly by -30 t CO_2e in total over 50 years.

Regarding a life cycle of 50 years, nearly all the construction materials implemented in the Urban Mining Index endure the supposed time span. Only the vapor barriers (lifespan 40 years) and the 100% cotton felt (lifespan 25 years) at the interior walls and the ceiling soffit need to be replaced once. The global warming potential value for the replacement is therefore close to zero. The service life of technical components is shorter than that of building elements. Except for the ventilators and the exhaust air pipes, all components must be replaced 1-2 times within 50 years. Almost all technical components are bundled in the technical core. The pipes are left visible wherever possible. The easy accessibility to the elements in the technical core enables quick and easy repair and replacement of necessary individual components. Thus, the technical components cause 42,47 kg CO_2e.

RoofKIT primarily uses electricity directly produced by the PVT collectors or electricity stored in the batteries during surplus generation periods. This approach, together with an intelligent energy management system which optimizes the self-consumption of electricity, leads to only 1.009 kWh of electric energy needed from the grid per year. Weighted with an emission factor of 200 g CO_2e/kWh this results in approx. 10 t CO_2e over 50 years. On the other hand, RoofKIT generates an electricity surplus of 5.040,8 kWh. Considering the same emission factor as for grid electricity, 1 t CO_2e can be subtracted over the 50-year emission balance during the usage phase.

For waste processing and disposal (phases C3 and C4, EN 15978), the end-of-life scenario Reuse or Recycling was selected for some elements, such as for the copper roof. For most renewable resources, thermal recycling was assumed as a standard scenario and greyed out in the UMI-Tool. According to EN 15978, the carbon balance for wood must be balanced over the entire life cycle and thermal utilisation is automatically taken into consideration in phase C. In this case, this would mean that all CO_2 sink potentials in phase C are cancelled out and 54 t CO_2e are emitted

Since RoofKIT does not envisage thermal recycling, the emissions of this phase were manually set to zero for all renewable raw materials, like wood, seaweed insulation, cellulose plates, and the cotton felt. This assumes, for example for the used old wood, that the materials will be reused as long as possible and then composted at some point of the life cycle, but not burnt. The nutrients end up in the soil and the cycle starts all over again. For the technical components, no end-of-life scenario could be selected in the eLCA tool. Here, the value is lower than 1,7 kg CO_2e for C3 and C4.

In total, the global warming potential adds up to emissions of approx. -15,9 t kg CO_2e during manufacturing, usage phase and demolition. Especially the wooden construction serves as carbon sink and reduces the carbon footprint significantly. The potential for recycling and reuse outside the system boundaries (phase D, EN 15978) is -19 t CO_2e for the structural building elements and -5,1t CO_2e for the technical elements in material terms.

As mentioned before, the above data for the global warming potential within the life cycle of the HDU regarding the structural elements were taken from the Urban Mining Index Tool. The tool evaluates the circularity potential of the main construction elements, taking into account the dismantling possibility and the (closed) loop potential, as well as the return of all materials into the technical or biological cycle. According to this method, RoofKIT achieves a recycling potential of 101.7 % for the HDU.

6. **Conclusion**

The paper presents a building concept to be realized within the SDE 21/22 which combines ambitious targets in terms of CO_2 neutrality during the operation of the building unit by harvesting solar energy, and with regard to minimizing the carbon footprint of the construction itself over the whole lifecycle. Besides the care about the environmental impact, occupants' well-being and comfort is of utmost importance for the design of the building.

Thermal comfort in winter is achieved by high-level insulation of the building envelope, ventilation heat recovery and a radiant heating system. The decentralized ventilation systems were integrated into the facades in a way that draft does not affect the occupants. In summer, passive cooling guarantees a comfortable indoor environment; the implementation of thermal mass into the lightweight construction has a crucial role as it stores heat over the day which is then discharged during the night via natural ventilation through the buoyancy effect. Simulations showed that indoor temperatures are within the boundaries of the adaptive comfort model most of the time.

With regard to air quality, the first step was to select non-/low-emitting materials for the interior which reduces the concentration of substances in the air to mainly human-based pollutants. These are continuously discharged by the mechanical ventilation in winter and by manual window opening outside the heating season. A monitoring system visualizes the CO_2 concentration for this purpose and reminds the user to open a window. Additionally, loam surfaces buffer and balance humidity peaks in the main living areas.

With 95% coverage of the HDU's electricity consumption by PV, carbon neutrality is almost reached on an annual basis. The energy concept for the whole building also shows how to tap further energy "sources" by using waste heat from grey water and biowaste to extend the idea of circular economy to technical systems in the building.

One of the outstanding features of RoofKIT is the consistent urban mining approach by reusing materials and (building) components wherever possible, as well as integrating recyclable natural and cultivated materials into detachable constructions. Prefabrication transforms urban mining into an industrialized building process that helps to minimize the number of used materials not only during the planning process but also during fabrication. The global warming analysis results in a negative CO_2e emission balance if thermal utilization for the removal phase can be avoided for renewable resources and recycling and reuse is consequently followed in the building concept.

The RoofKIT team wants to set an example for future building. An integrated design strategy yields to utilize all available possibilities with regard to materials, construction and energy supply in order to set a sign for high quality architecture – also as a symbiosis of 'old' and 'new'. A monitoring campaign during the two weeks of the SDE competition in Wuppertal and further research on the energy performance of the building unit in Karlsruhe will show whether the whole concept could be successfully transferred into practice and what are the lessons learned to this regard.

Acknowledgments

The project is supported by funding from the German Federal Ministry for Economic Affairs and Climate Action (BMWK, FKZ 03EGB0032), the Karlsruhe Institute of Technology (KIT), the Baden-Württemberg Ministry of Food, Rural Areas and Consumer Protection, as well as cash and in-kind contributions from numerous sponsors.

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