Impacts on the Embodied Energy of Rammed Earth Façades During Production and Construction Stages

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Abstract

Rammed earth is a technique for constructing sustainable buildings, with a low energy demand encompassing the whole life cycle of buildings. Soil from the excavation can be compressed on-site to build a façade. Due to its hygroscopic and thermal properties, rammed earth façades stabilise indoor comfort, which potentially supports the minimisation of use of mechanical systems. In order to reduce the energy demand for the entire life cycle of buildings, the embodied energy must be taken into account. Databases, such as the German Ökobaudat, provide data for a life cycle assessment (LCA). For rammed earth, aggregated data at product stages A1-A3 are provided, but transport, which is included in stages A2 and A4, and construction processes at stage A5 are barely documented. Thus, the energy demand for transport, production, and construction of two rammed earth façades was measured. The results are documented in this paper, which provides a more thorough understanding of the entire building process and helps to expand the database. One can conclude that transportation has the largest impact on the embodied energy of rammed earth façades, so it's essential to use local material. Furthermore, the results illustrate the implication of transport on a life cycle assessment, as well as for other constructions.

Keywords

embodied energy, Life Cycle Assessment, stages A1-A5, transport, rammed earth façade

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1 INTRODUCTION

Since 1977 (WSchVO, 1977), German policies have supported the decrease of the energy demand of buildings in order to reach national and international climate targets. National regulations, like EnEV, are still enforcing the reduction of the operational energy of buildings. However, the embodied energy of buildings has barely been considered. In order to minimise the energy demand over the entire life cycle of a building, current research(Auer, Santucci, Knaack, & Hildebrand, 2015; Meex, Knapen, Hildebrand & Verbeeck, 2018; Markus, Jensch & Lang, 2014) and practice, such DGNB certifications since 2009, are now also focusing on the embodied energy.

In this regard, rammed earth façades provide a sustainable approach because of their thermal and hygroscopic properties, their low embodied energy, and their high recycling potential. The material has a high thermal mass due to its fairly high heat capacity ($c_p \approx 850$ J/kgK), high thermal conductivity ($\lambda \approx 1.1$W/mK), and high density ($\rho \approx 2300$ kg/m^3). Thermal mass stabilises the indoor climate by buffering fluctuating heat loads related to the outdoor temperature, solar gains, and internal loads. A passive building design activates thermal mass by natural night-time ventilation during hot summer periods. In addition, rammed earth also buffers moisture peaks due to its hygroscopic properties. The adsorption of moisture is four times higher than that of mineral building materials, e.g. gypsum plaster (Klinge et al., 2016). The adsorption and desorption of moisture is self-regulating. Thus, rammed earth façades promote a healthy and comfortable indoor climate. Respiratory diseases caused by a dry climate or mould formation caused by a humid climate can be reduced. Furthermore, Osanyitola & Simonson (2006) showed that 2% of the total heating energy and 11% of the total cooling energy in the continental climate region of Germany can be reduced by combining hygroscopic materials with a well-controlled HVAC system. Another phenomenon results from the heat of adsorption, which is released by the adsorption of moisture and heats up the material (and vice versa). This hygrothermal potential is reversible and decreases the surface temperature during desorption.

As seen, the properties of building materials can significantly reduce energy demand for building operations. Furthermore, literature data based on the German database Ökobaudat show that the energy demand of the raw material supply, the transport to the production site, and the manufacturing of rammed earth is about 70% lower than that of conventional façades, e.g. brick façades. As the production and construction process of rammed earth differs to conventional façades and has not yet been fully explored, this study analyses the impacts on the embodied energy of rammed earth façades in production and construction including transportation.

2 THEORETICAL BACKGROUND: THE EMBODIED ENERGY OF RAMMED EARTH FAÇADES

2.1 ACTUAL STATE OF SCIENCE

The German database Ökobaudat is based on DIN EN 15804. This standard describes the life cycle of buildings from the production and construction stage to the end of life by dividing it into different stages:

- A1-A3 product stages
- A4-A5 construction process stages
- B1-B7 use stages
- C1-C4 end-of-life stages
- D reuse, recovery, recycling potential

The database provides data to calculate the embodied energy for thousands of building materials, though many data sets are not complete. Stages A1-A3 are usually provided as aggregated data, including the raw material supply (A1), the transport to the production site (A2), and the production (A3). Aggregated data sets cannot be divided into stages due to a lack of information. In general, stages A4 and A5 are insufficiently documented. Values for stage B are given by standard calculation of energy certificates or thermal simulation. However, data for the end of life and the recycling potential of building materials is incomplete. For rammed earth, aggregated data for stages A1-A3 only is available (see Fig. 1).

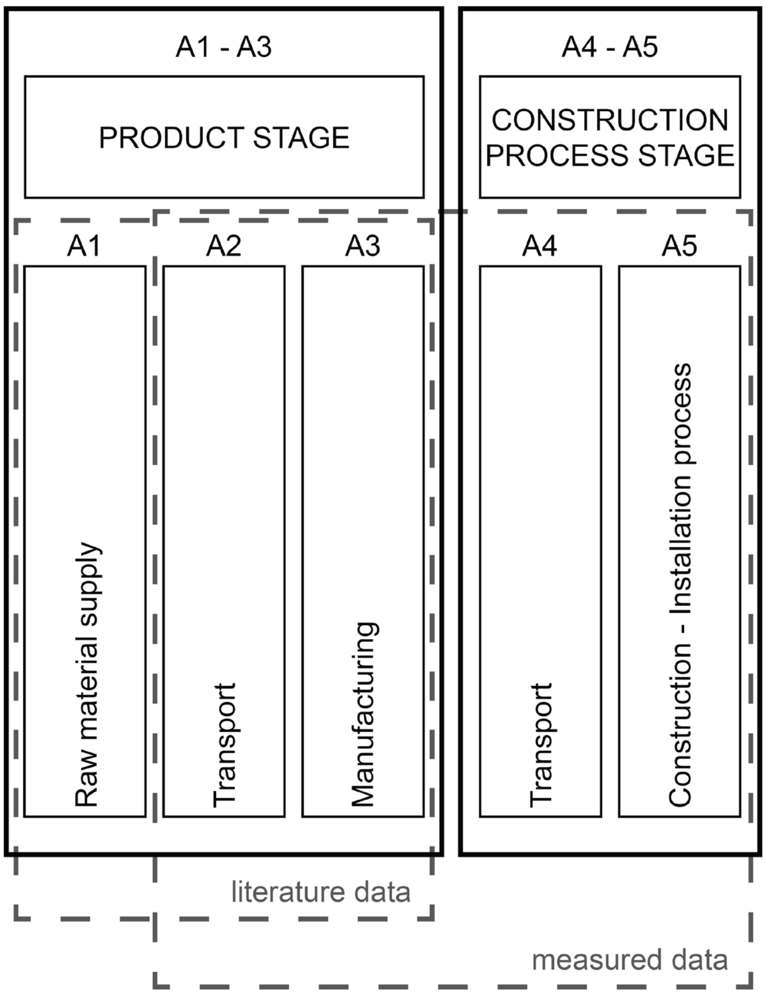

FIG. 1 For rammed earth, aggregated literature data at stage A1-A3 is available. Stages A2-A5 are measured in this paper. Figure based on DIN EN 15804

2.2 METHODOLOGY, FUNCTIONAL UNIT, SYSTEM BOUNDARIES

This paper focuses on the primary energy demand at stages A1-A5 of rammed earth façades (see Fig. 1). Two case studies (Variant A and B, see Chapter 2.3) are selected because of their different production (on-site vs. off-site) and construction processes (monolithic and double-shelled), as well as the origin of the excavated earth (local vs. non-local). At first, the embodied energy for stages A1-A3 is calculated based on literature data representing the status quo. In order to reference these results to conventional façades, stages A1-A3 are also calculated for theoretical brick façades (Reference A and B, Chapter 2.3) with similar thermal performance. Subsequently, the primary energy demands of stages A2-A5 are measured for Variant A and Variant B. Stage A1 could not be measured because of a lack of data due to external material supply. However, the primary energy demand for stage A1 was found in previous literature research. Finally, the results for stages A1-A5 are referenced against their References A and B.

The data for the conventional brick façades is provided by an Austrian brick association Initivative Ziegel (2015) and is based on ÖNORM EN 771-1 (2005) and ÖNORM EN 15037-3 (2001). Data that was found to be missing in Ökobaudat (2017)are completed with comparable data sets of other building materials and data to complete missing transport distances are based on Kellenberger & Althau (2008)and Binz, Erb & Lehmann (2000). The primary energy demand listed in (Initiative Ziegel, 2015) is about 40% lower than other literature data, e.g. (AG Mauerziegel, 2015). Thus, the comparison between the references and variants represent a worst-case scenario for rammed earth façades.

The total primary energy demand (PE) is measured and calculated, including renewable (PERT) and non-renewable (PENRT) primary energy (PE = PERT + PENRT). Primary energy factors f_{PE} are given in Table 1. In order to facilitate the comparison of the results with different façade systems, the functional unit is $1m^2$ of an opaque façade component. The density and mass are taken into account. No other properties, e.g. heat capacity, U-Value, or hygroscopic performance are taken into account. Specific construction processes related to outdoor climate conditions, e.g. protection against freezing, are excluded. The PE for transportation ($PE_{transport}$) is calculated as a product of the mass, *m*, in kg, which is transported over a distance of *x* in km multiplied by the energy factor of the vehicle . A truck with an average load of 24 tons (Ökobaudat 2017, data set 9.3.01) is assumed.

$$PE_{transport} = x \cdot m \cdot f_{vehicle} \qquad (1)$$

ENERGY CARRIER	F_{PE} [-]	REFERENCE
German electricity mix	2.80	(DIN18599-1, 2016)
Diesel	1.22	(Frischknecht, Et. Al, 2012)
Transport vehicle	f_{PE} [MJ/1000kgkm]	
Truck (average load 24 t)	0.74	(Ökobaudat 2017, data set 9.3.01)

TABLE 1 Primary Energy Factors

2.3 DESCRIPTION OF VARIANT AND B AND THEIR REFERENCES

Variant A (see Fig. 2) is the world's largest contemporary rammed earth façade, with a total area of 2790 m^2, a thickness of 45 cm, and consists of 667 pre-fabricated rammed earth units. It is the façade of a Swiss industrial production and storage unit for a herbal confectionery company. To store herbs, the indoor temperatures can vary between 5 °C and 28 °C, while relative humidity has to be kept at 50%. Due to the temperature range of 23 K, a U-Value of 1.7 W/m^2K is acceptable to comply with Swiss code requirements for energy conservation. The rammed earth façade guarantees a fairly constant indoor climate with 50% relative humidity (Herzog de Meuron, 2015). The hygroscopic, self-regulation effect of rammed earth supports the design of a smaller HVAC system and still provides the required conditions. The production of rammed earth façade elements is located close to the building site (3 km).

In order to compare the results of Variant A with a conventional façade of similar thermal performance, a brick façade with a thickness of two bricks is considered (see Fig. 2, Reference A). As bricks are fabricated in standard widths of 24 cm, the thickness of the wall is 48 cm. Due to this and the material characteristics of the bricks, the wall has a U-Value of 1.5 W/m^2K, which is comparable with Variant A. The bricks have a density of 2000 kg/m^3 and a specific heat capacity of 1.00 kJ/kgK (see Table 2).

Variant B (see Fig. 2) is the largest rammed earth façade in an office building, with a total area of 1417 m^2 and a thickness of 68 cm. It consists of 384 pre-fabricated rammed earth units. The self-supporting façade is three floors high and is fixed to the floor plate every 4 m in order to avoid folding. The plasticity of rammed earth enables a monolithic and jointless façade. In order to improve thermal performance, the U-Value has to be at 0.35 W/m^2K. This has been achieved using a double-shelled construction with foam glass granulates in the centre. The inner shell contains a capillary conditioning system, which activates the thermal mass of the façade. The capillary conditioning system is neglected in this study. The massive walls ensure a relatively constant indoor climate due to the thermal mass. The production of the pre-fabricated rammed earth façade units is done on-site.

As it follows, Reference B (see Fig. 2) is a theoretical conventional façade with a similar U-Value of 0.34 W/m^2K. It is a brick wall of 24 cm with an expanded polystyrene (EPS) insulation of 10 cm. Consequently, the thermal mass is less than that of Variant B. The impact on the embodied energy due to different thermal mass will be discussed in Chapter 3.

	VARIANT A	REFERENCE A	VARIANT B	REFERENCE B
Density ρ [kg/m^3]	2350	2000	2150	2000
Specific heat capacity cp [kJ/kgK]	0.85	1.00	0.85	1.00
Mass per m^2 façade [t/m^2]	1.06	1.04	1.28	0.57
U-Value [W/m^2K]	1.70	1.50	0.35	0.34

References A and B are calculated based on literature for density (Ökobaudat, 2017) and heat capacity (ÖNORM B 8119-7, 2013)

TABLE 2 Physical properties of Variant A and B and References A and B. Data for rammed earth is based on measurements *(ZAE Bayern, 2011)*

2.4 DESCRIPTION OF PROCESSES IN STAGES A1-A5

The production and construction of rammed earth façades are different to a conventional brick façade. To point out the differences, the two process chains are described in the following:

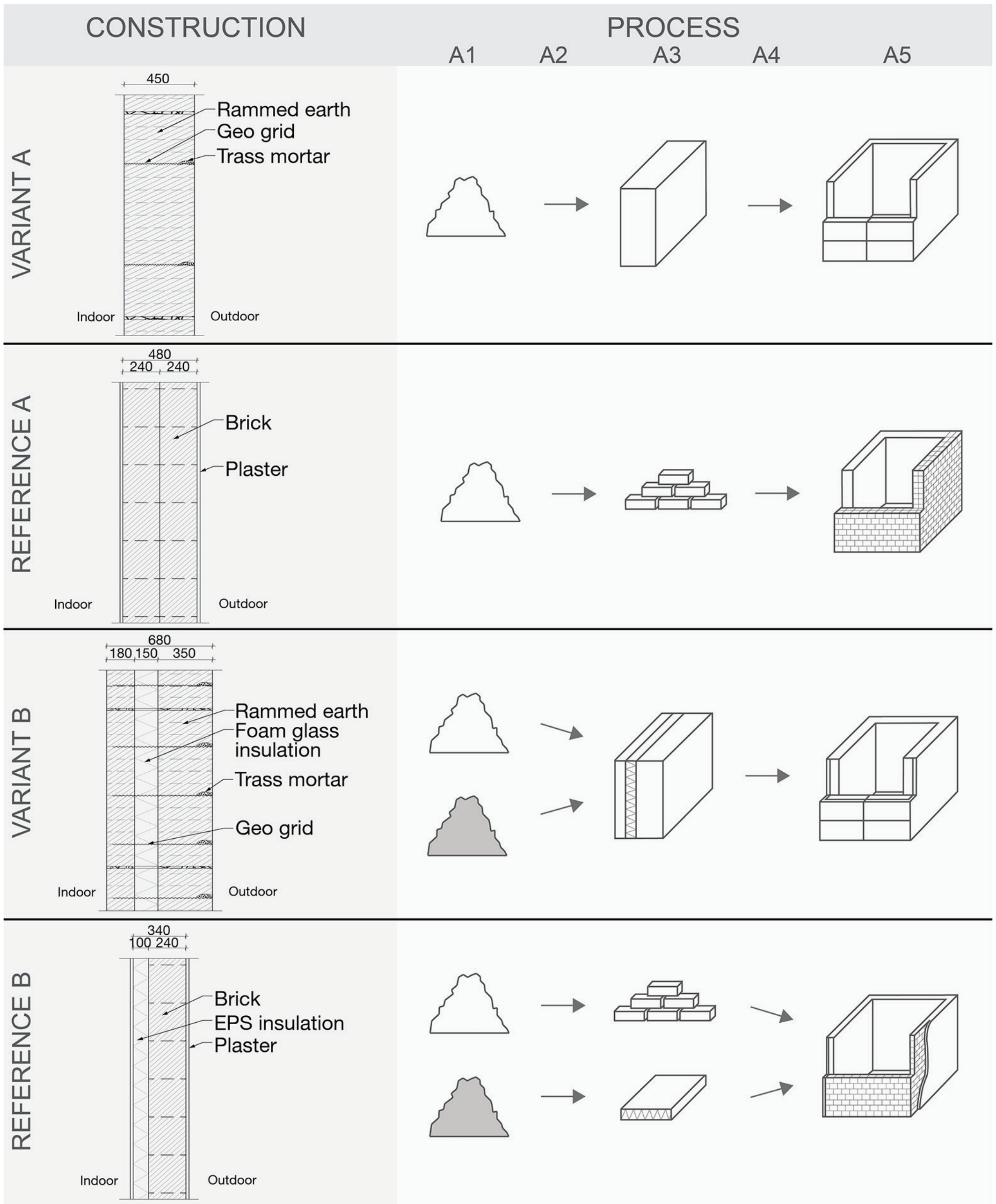

FIG. 2 Construction of Variant A, Variant B, and their references A and B, and their production and construction processes

The first step to build a brick façade is to excavate the raw materials (A1) to produce a brick. Bricks are based on similar raw materials as rammed earth: clay, sand, lime etc., which have to be extracted from a mine. In contrast to rammed earth, the other materials must be screened and packed at the mine and transported to a factory, where they are baked (A2) at around 1000 °C. After the production of the brick (A3), it is transported to the construction zone (A4) to build the façade (A5). In stage A5 all building materials (bricks, mortar, insulation, and plaster) are brought together to build the entire façade.

The process of rammed earth façades is less complex; excavated soil, e.g. from the building pit, can be used to produce a rammed earth façade. The excavated soil consists of raw materials such as clay and gravel. Even earth mixtures that cannot be used for the fabrication of bricks (based on processed clay) or concrete (based on processed gravel) are usable. Depending on the quality of soil, some additional materials have to be supplemented. Thus, the composition of each rammed earth façade is individual. Geo grids stabilise the entire façade and trass mortar lines are set every 40-50 cm to protect the façade from erosion. In the pre-fabrication process, single façade units with weights of up to 5 tons and lengths of 3.5 m are produced in three steps:

- mixing process
- ramming process
- drying process

As the production site can be installed flexibly, the transport distance to the building site (A4) can even be reduced to zero if it is on-site. At stage (A5) the façade units are piled up into an entire façade.

2.5 MEASUREMENT CONCEPT

Fig. 3 and Table 3 describe the measurement concept of Variant B. For stage A2, the total transport distance is measured based on delivery notes. Stage A3 considers the whole production process, including mixing, ramming, and drying. Due to installation issues, the mixing plant and the compressor are measured by electric meter 1, and the material turner, the material feeder with ramming robot, and cutting unit are measured by electric meter 2. The diesel consumption of the telescope loader and the fork lift is measured and scaled by the number of operating hours. To calculate the total distance of stage A4, the distance between the production and building site is multiplied by the amount of trips that a truck has to make to transport all façade units to the construction site. The embodied energy for the construction is measured by the diesel consumption of the mobile crane and scissor lift.

The measurement concept of Variant A is less complex: Transport stages A2 and A4 are measured like stage A4 of Variant B. The mixing, ramming and drying process of stage A3 are not measured separately. Stage A5 follows the methodology of Variant B.

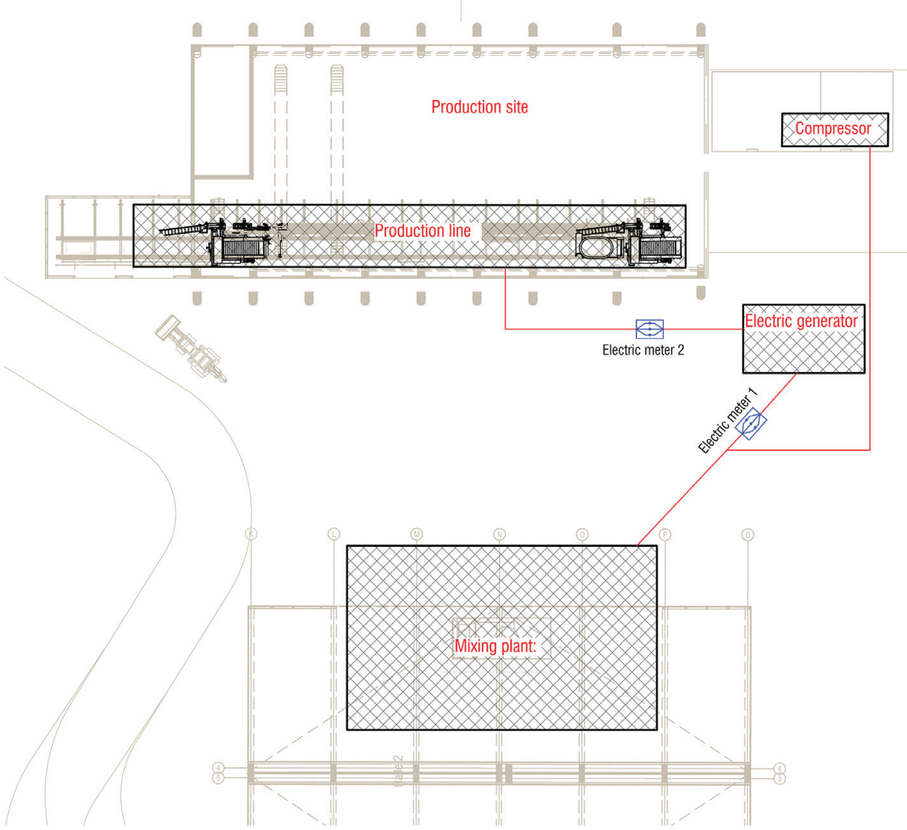

FIG. 3 Installation of electric meter at the production site of Variant B

	STAGE	DATA RECORDING
A2	**Transport to production site**	
	Material transports	Delivery notes
A3	**Mixing process**	
	Mixing plant	Electric meter 1
	Material turner	Electric meter 2
	Telescope loader	Diesel consumption and operating hour meter
A3	**Ramming process**	
	Material feeder with ramming robot and cutting unit	Electric meter 2
	Compressor	Electric meter 1
A3	**Drying process**	
	Fork lift	Diesel consumption and operating hour meter
	Heating in winter	Excluded
A4	**Transport to building site**	
	Distance of journey	Geodata
	Amount of truck trips	Counting
A5	**Construction**	
	Mobile crane	Diesel consumption and operating hour meter
	Scissor lift	Diesel consumption and operating hour meter

TABLE 3 Measurement concept, documentation of data recording for stage A2-A5 for Variant B

3 RESULTS

3.1 LITERATURE STUDY AT STAGES A1-A3 FOR RAMMED EARTH AND BRICK FAÇADES

The embodied energy for Variant A and B and their References at stages A1-A3 is calculated based on literature (Ökobaudat, 2017). The results are shown in Fig 4. Variant A (150 MJ/m^2) requires 70 % less PE than Reference A (498 MJ/m^2). The main reason for the lower primary energy demand is that rammed earth façades are not baked. Bricks are baked at temperatures of around 1000 °C, which requires a huge amount of energy. Variant B (395 MJ/m^2) requires only 21% less than Reference B (500 MJ/m^2) because of the massive construction of Variant B (1.28 t/m^2) compared to Reference B (0.57 t/m^2).

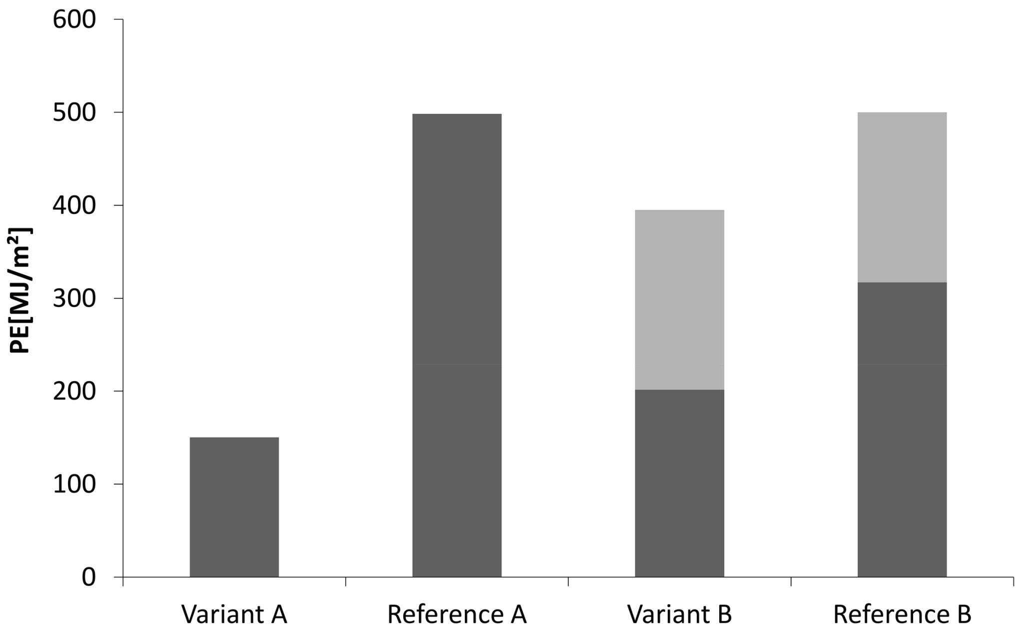

FIG. 4 Results of literature study on the primary energy demand at stage A1-A3 based on (Ökobaudat, 2017). The light coloured part represents the impact of the insulation

Another reason for the higher PE of Variant B compared to A is the extra energy demand for the production of the foam glass insulation. The results show that the impact of the insulation material is significant. Almost half of the total embodied energy of Variant B is due to the insulation material.

3.2 LITERATURE STUDY ON PRIMARY ENERGY AT STAGE A1

Due to external material supply the energy demand at stage A1 could not be measured. Hence, a literature study on the raw material supply is done to quantify stage A1. The entire primary energy demand, which is needed to excavate soil or to prefabricate additional materials, e.g. geo grids or foam glass, is taken into account. The total primary energy demand of Variant A is 167 MJ/m^2 and for Variant B is 435 MJ/m^2. In Table 4, the impact of each material on the PE at stage A1 is documented. As seen, pre-fabricated materials, e.g. for clay powder or foam glass, have a crucial impact on the PE even with small mass fractions. In comparison to section 3.1, it becomes apparent that the aggregated data set assumes an energy efficient production and construction process and potentially excludes pre-fabricated materials.

Building material	VARIANT A		VARIANT B		Data
	Mass fraction [%]	PE [%]	Mass fraction [%]	PE [%]	
Excavated earth	30.30	0.00	58.51	0.00	N/A, assumption recycling material
Excavated raw clay	22.97	5.93	8.70	1.04	Excavation (Ökobaudat, 2017), preparation (supplier information)
Clay powder	0.98	41.17	2.59	11.25	(Ökobaudat, 2017) 1.1.04 clay powder
Gravel/marl	43.50	27.89	14.55	2.09	(Ökobaudat, 2017), 1.2.01 gravel 2/32
Sand	1.69	0.20	2.76	0.40	(Ökobaudat, 2017), , 1.2.01 sand 0/2
Trass mortar	0.54	16.36	0.45	1.90	EPD-RHT-2011111-D
Geo grid	0.01	8.45	0.10	30.72	(Ökobaudat, 2017), , 6.6.07 Fortrac® T
Crashed lava stone	-	-	9.55	8.09	(Ökobaudat, 2017), , 1.2.02 crashed stone 2/15
Foam glass	-	-	2.80	44.51	EPD-MIS-20150019-IAA1-DE
Total PE [MJ/m²]		166.69		434.62	

TABLE 4 Results of literature study on primary energy demand at stage A1 for Variant A and B

3.3 MEASUREMENT OF THE PRIMARY ENERGY AT STAGES A2-A5

Fig. 5 shows the results of the measurements for stages A2 to A5. As seen, transport has the highest impact on the embodied energy, especially for Variant B at stage A2. The reason for this is that 1061 tons of excavated soil are transported over a total distance of 9143 km, which involves about 5200 MJ/m^2. The excavated soil is taken from a tunnel construction (223 km away) as recycling material instead of being transported to a landfill. In a holistic view, it has to be taken into account that the transport to a landfill also demands energy, which is considered in the form of a credit. In this case, the credit is about 25% due to the distance to the landfill of about 60 km (supplier information). In this regard, the primary energy demand of stage A2 is about 3833 MJ/m^2. For Variant A, more than 98% of the materials are transported for distances of less than 10 km to the production site (see Table 6). Only some additional components (<1% of mass fraction) such as trass mortar and geo grids are transported over longer distances (>100 km). Thus, the primary energy demand of stage A2 is lower than that of Variant B (209 MJ/m^2).

The transport from the production to the building site (stage A4) for Variant A requires almost 291 MJ/m^2. The reason for this is that 667 façade units with a total mass of more than 2956 tons are transported for a distance of only 3 km. In this context, the mass and not the distance is the crucial point. The primary energy demand of Variant B is zero due to its production on-site.

Considering both transport stages, A2 and A4, the impact of transport is more than 55% of the total embodied energy (A1-A5) for Variant A and more than 84% for Variant B. In Table 5, the total distance of all materials and all journeys is specified on a 1 m^2 façade surface in order to compare the measurement results. The values consider the total mass of each façade (Variant A: 2956 tons, Variant B: 1813 tons) due to the number of journeys taken by a truck with an average load of 24 tons. Depending on its production process, the PE required by the transport can be shifted from stage A4 to A2 (see Fig. 5). Thus, an aggregation of stages A1-A3, can hide transport energy by obtaining further information about transport distances at stage A2. The aggregation can limit the clarity of data.

For stage A3, the primary energy for Variant A is 151 MJ/m^2 and for Variant B 174 MJ/m^2. The values are about the same as calculated literature values for stage A1-A3 (see section 3.1). Thus, literature data assumes less primary energy demand as is measured in reality. This leads to the conclusion that the aggregated data set of ÖBD is based on a building, where the excavated soil for the building foundation is rammed directly on-site without processing the soil and using additional material. Thus, the energy demand at stages A1 and A2 can be neglected. This assumption is valid for a smaller family house, such as 'Wohnhaus Rauch' (Mattli, Klauz, Plüss, & Menti, 2010).

The foam glass granulates of Variant B are rammed during the production process of the façade units. Thus, there is no further energy demand for installing the insulation (A5). The PE at stage A5 of Variant A (84 MJ/m^2) is slightly lower than that for Variant B (95 MJ/m^2) because of the lighter façade units. About 80% of the PE is consumed by the use of a crane to pile up the units and about 20% is due to the transport of the façade units to the crane.

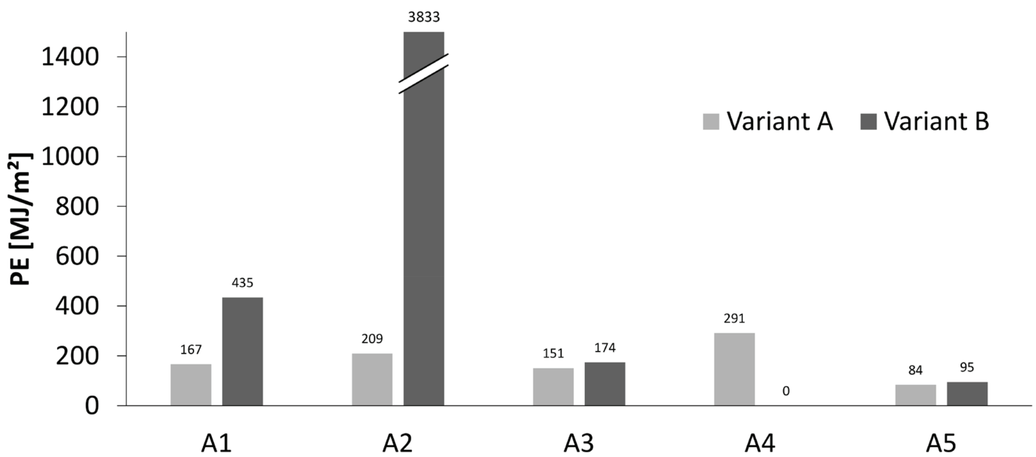

FIG. 5 Results for primary energy demand at stage A1-A5. Stage A1 is based on assumptions and literature data, stages A2-A5 are measured.

	A2 [km/m^2]	A4 [km/m^2]
Variant A	0.61	0.13
Variant B	7.93	0.00

TABLE 5 Transport distance referenced on 1 m^2 of an opaque façade component. Measured data for Variant A and Variant B.

BUILDING MATERIAL	VARIANT A			VARIANT B		
	Mass fraction [%]	Transport distance A2 [km]	PE fraction [%]	Mass fraction [%]	Transport distance A2 [km]	PE fraction [%]
Excavated earth	30.30	8	33.50	58.51	223	97.35
Excavated raw clay	22.97	3	7.21	8.70	93	1.18
Clay powder	0.98	426	1.56	2.59	125	0.18
Gravel/marl	43.50	8	56.75	14.55	6	0.17
Sand	1.69	8	0.10	2.76	29	0.03
Trass mortar	0.54	436	0.88	0.45	142	0.01
Geo grid	0.01	19	0.00	0.10	321	0.02
Crashed lava stone	-	-		9.55	12	0.15
Crushed foam glass	-	-		2.80	361	0.92
Total PE [MJ/m^2]			209			3833

TABLE 6 Mass fraction, transport distance (one way) and primary energy (PE) fraction for stage A2 for Variant A and Variant B

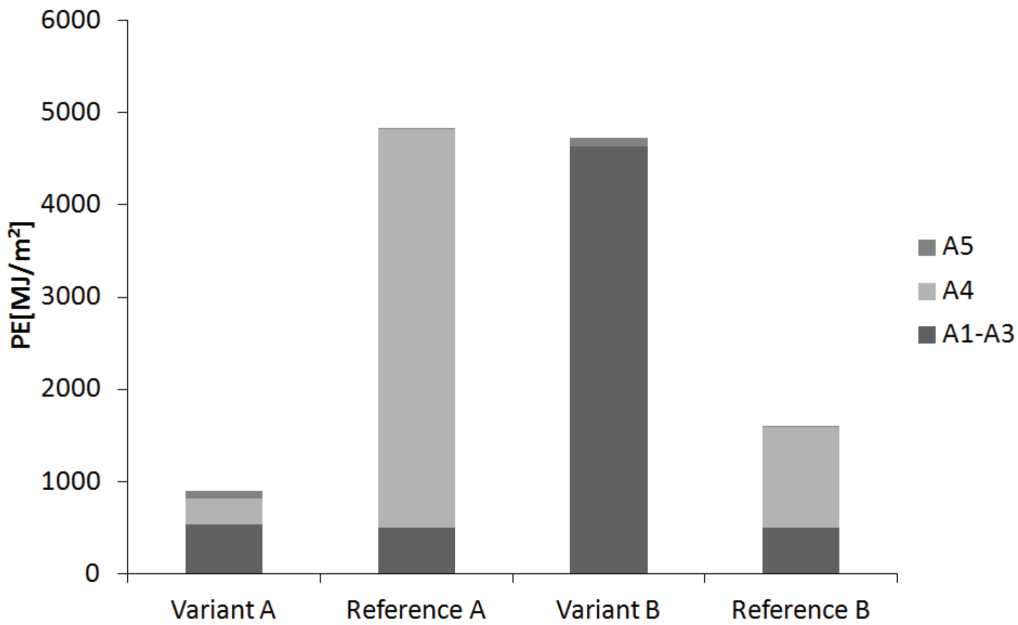

FIG. 6 Total results for PE in MJ/m^2 at stages A1-A5 for Variant A and B (A1 based on literature study, A2-A5 based on measurement data) and their conventional brick references Reference A and B (based on literature data, worst case scenario for rammed earth)

3.4 SUMMARY FOR STAGES A1-A5 FOR RAMMED EARTH AND BRICK FAÇADES

In Fig. 6, the results of Chapter 3.2 and Chapter 3.3 are summarised and compared with literature data for Reference A and B. As described in Chapter 3.3, the literature data assumes less primary energy demand than that measured in reality. Referring to the proportions of Fig. 4, and the more complex production process of brick façades (see Chapter 2.4), it is expected that the PE at stages A1-A3 for Reference A and B is higher. However, this uncertainty does not change the conclusion of this study that transport has a huge influence on the embodied energy of rammed earth façades.

The embodied energy of the rammed earth façade A is more than 80 % less than its conventional reference. Compared to literature study at stage A1-A3 (see Chapter 3.1) the potential at stages A1-A5 is even higher. However, this conclusion is only valid for local material, as the case study B shows: The transportation requires almost three times more energy than its conventional reference at stage A1-A5. This long transportation of heavy material has a significant impact on the embodied energy. The impact is even higher than the production energy of the insulation (see Fig. 4). This effect is also represented in the comparison of Reference A and B at stage A4: As Reference A is a double brick wall, double the amount of bricks ($2m$) have to be transported over double the distance ($2x$) which causes four times PE of Reference B (see equation (1)).

4 CONCLUSIONS

In general, rammed earth façades provide sustainable solutions with a low embodied energy demand. In the considered projects, the production requires only about 151-174 MJ/m^2. As case study A shows, the embodied energy at stages A1-A5 is more than 80% less compared to its conventional brick reference. However, this conclusion is only valid when using local material, as case study B shows. The impact of transportation is significant, especially for massive constructions in low tech designs with a high thermal mass. Considering both transport stages, A2 and A4, the impact of transport is more than 84% of the total embodied energy (A1-A5) for Variant B.

Furthermore, the comparison of the aggregated literature data with the measurement results shows that aggregation can hide the impact of transportation (A2) in a life cycle assessment. It is critical to obtain information about transport distances at stage A2, when aggregating the PE at stages A1-A3. The study also identifies the need to quantify stages A2 and A4, at least for all materials that contribute to the superstructure of buildings.

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