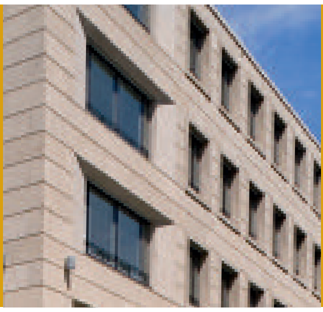
Sustainability Study



Environmental Life Cycle Assessment of Natural Stone and Glass Façades

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Sustainable Building with Natural Stone

Natural stone stands for long-term value preservation and durability. Both aspects are of high priority in contemporary architecture. Natural stone was not only the preferred building material of our ancestors; it is also an essential element of modern architecture. New processing methods and developments in masonry allow for a wide range of uses and facilitate in particular the construction of aesthetically sophisticated façades.

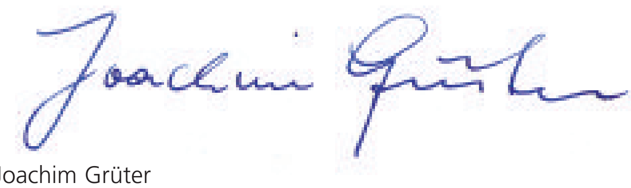
The sustainability of buildings has become an important issue. By publishing its Sustainable Building Guidelines, the federal government has defined clear political goals in order to noticeably lower Germany's CO_2 emissions in the upcoming years. Since the energy use of buildings constitutes a major fraction of overall CO_2 emissions, employing sustainable and energy-efficient construction methods has become crucial.

Unprocessed building materials such as natural stone are thus moving into the limelight. For the production of natural stone no energy is required: it is supplied by nature. Only the quarrying and processing of natural stone consumes energy. And what is more, if indigenous stone is used, routes of transportation are short.

Recent reports corroborate that solid construction techniques are superior to building with glass. The Bavarian Audit Office for instance published a directive that suggests that glass façades are more wasteful and more costly than solid construction and should only be used in well-justified exceptional cases. Studies of the Institute Wohnen und Umwelt in Darmstadt determined that the energy efficiency of buildings with glass façades merely attains the level of uninsulated buildings from before World War II.

These unambiguous facts as well as the increased interest in sustainable construction have inspired us to commission the prestigious consulting agency PE International to carry out a study comparing the sustainability of natural stone façades with that of glass façades. The following report examines the environmental and economic effects of natural stone façades over their entire life cycle and measures them against their glass counterparts.

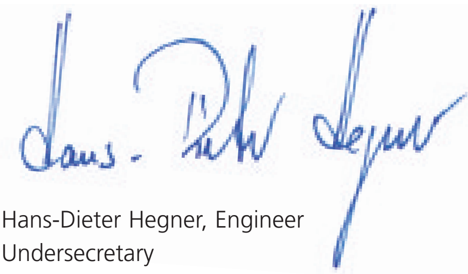
In the hopes of promoting sustainable building, I commend this report to a large expert as well as lay readership.



Joachim Grüter
President of the German Natural Stone Association

Sustainable Building – the Federal Government's Perspective

In its coalition agreement, the current administration has committed itself to further developing the national sustainability strategy within its tried and tested institutional framework.
In this context, the Federal Ministry of Transport, Building and Urban Development (BMVBS) has taken on the task of improving the quality of construction by integrating sustainability concepts even more and by modeling good practices with its own buildings. To achieve this goal, the BMVBS and the other interested parties from the Round Table on Sustainable Building together with the German Sustainable Building Council have further refined the principles and directives for the evaluation of sustainable buildings.
The resulting proposal allows for a comprehensive scientific characterization and assessment of building quality with for the most part quantitative methods. Since 2009, the rating system has been freely accessible to architects, planners and principals and others interested in construction on the web pages of the information portal on sustainable building of the BMVBS (www.nachhaltigesbauen.de). With this rating system, a scientifically sound, quantitative and holistic evaluation procedure for office and administrative buildings that enables a well-balanced assessment of the different dimensions and aspects of sustainability has become available. Its foundation is a life cycle assessment that combines an analysis of environmental impact with life cycle costing. Current building projects of the federal government are already referencing the framework of the rating system. The federal government also works with other public entities as well as the housing industry on adapting the sustainability rating system for residential buildings, schools and civil engineering structures.
The availability of transparent and verifiable information regarding the environmental and health impact of building materials is a precondition for the evaluation of buildings. The Construction Products Regulation of the EU, which is currently still being discussed, is supposed to eventually make it possible to deliver a precise assessment of the sustainability of individual products. In this context, Environmental Product Declarations are a valuable tool to demonstrate resource efficiency. They are based on an internationally coordinated declaration framework that defines in particular uniform general and marginal conditions as well as environmental indicators such as a product's contribution to the greenhouse effect or its impact on the atmospheric ozone layer.
Transparent information on the environmental impact of building materials constitutes an essential contribution to putting the national sustainability strategy in practice. Here the building industry and the BMVBS are engaged in a joint effort.



Hans-Dieter Hegner, Engineer
Undersecretary
Ministry of Transport. Building and Urban Development
Director of Division B13 "Construction Engineering, Sustainable Construction, Construction Research"

Introduction

In recent years, the relevance of sustainable construction has continuously increased. The term sustainable construction covers environmentally friendly and socially responsible planning and execution processes in construction as well as the operation of completed buildings.
In Germany the Round Table on Sustainable Building, which had been specifically created for this purpose, has worked on principles and guidelines for sustainable construction since 2001. One of the results of its work is for instance the Sustainable Building Guidelines of the Ministry of Transport, Building and Urban Development that are to be used as a planning guide for all public construction projects. In particular the activities of the German Sustainable Building Council have resulted in the development of a certification system for buildings that are planned and constructed in sustainable manner.
The German Quality Seal Sustainable Building is based on a catalog of about 50 criteria that allows the quantification of a wide range of factors.
Internationally, sustainable building is often labeled "green building". In Britain, such a certification system has been in use for many years. The BREEAM System also evaluates the environmental performance of buildings, taking into account social and health issues as well, but it does not assess economic performance. In the United States, the US Green Building Council has developed the LEED System. The system is now also used outside of the US for the planning of energy efficient and environmentally friendly buildings. To date, however, the LEED system does not use a complete life cycle assessment of the actual environmental performance of a building, but instead provides criteria for an environmentally motivated selection of building materials by rating them based on their discrete individual properties. For example, the LEED system assigns a particular rating to all materials and building products that need to be transported less than 800 kilometers to a construction site.

DGNB		UK GREEN BUILDING COUNCIL
GOLD	PLATINUM	OUTSTANDING EXCELLENT
SILVER	GOLD	VERY GOOD
BRONZE	SILVER	GOOD

The ecological quality of a building is best defined by doing an environmental life cycle assessment for the building. Façades substantially determine ecological quality, and they are of decisive importance for the heating and cooling needs of a building. The environmental life cycle assessment of a building includes an analysis of its ecological impact during production, waste disposal and recycling. Building evaluation based on a life cycle assessment approach is thus a crucial element of sustainable planning.
In the context of planning and building the OpernTurm in Frankfurt am Main, a certification based on the LEED standard was sought. The earliest planning for the OpernTurm had included glass façades. In the course of comparing different variants, however, the planners settled on the now actually realized natural stone façade. It is due to this natural stone façade that the OpernTurm received the coveted LEED gold certification by the U.S. Green Building Council. According to construction experts, the façade contributes crucially to the building's low energy requirements.

1 The Results at a Glance

The sustainability study demonstrates that natural stone façades have significant ecological and economic advantages compared to glass façades. The goal of planning and constructing sustainable buildings that will be awarded the sought-after DGNB or LEED certification means for façade construction that the exterior walls need to be compact, be insulated and covered with a natural stone cladding.

Part 1 – "Façade Variants in Natural Stone and Glass"

In the first part of the study by PE International, one square meter of a typical natural stone façade element based on the German standard DIN 18516-3 is compared with a glass façade element.
Over a period of 100 years, natural stone façades shows significant environmental advantages compared to glass façades. In sum, during production as well as the period of use, the energy requirements of natural stone façades are considerably lower than those of glass elements. If the entire life cycle is considered, glass façades consume three times as much energy as natural stone façades.
Just in the area of production alone, glass façades use up twice as much energy resources as natural stone. Natural stone façades also demonstrate ecological advantages in the area of other key environmental parameters, for example greenhouse emissions.
The results of the life cycle assessment during the period of use are overwhelmingly influenced by maintenance measures and in particular replacement cycles for the components used. During this period in their life cycle, natural stone façades with their relatively durable structural components use up only 50 percent of the energy required during production, while the maintenance of glass façades, whose elements need to be replaced frequently, results in a period of use that has the highest environmental impact of all phases of their life cycle. If the period considered is set at 100 years, individual construction elements of glass façades are replaced more than three times. That glass façades are cleaned with water, while important for economic considerations, is environmentally negligible.
The decisive value in the context of heat protection, the U-value, is considerably lower at 0.32 W/m^2K with natural stone façades than it is at 1.25 W/m^2K with glass façades. The transmission heat loss and therewith the heating requirements of a building with natural stone façades are thus significantly lower. The costs of the heat loss in the winter and the air-conditioning requirements in the summer are being considered in chapter 5.
When considering the period of use, it therefore becomes apparent that natural stone façades have a low ecological impact (resource use and emissions) in terms of the entire life cycle. With reference to the end of life, it is glass façades that receive ecological credit for their use of materials such as aluminum and synthetic materials, as channeling the latter back into the materials cycle avoids cost- and resource-intensive production.

The examined types of environmental impact of glass façades (GF) are between 60 and 360 % above those of natural stone façades (NSF):

Type of Environmental Impact	NSF : GF
Global warming potential [CO_2 equivalent; GWP]	1 : 2.5
Ozone depletion potential [R11; ODP]	1 : 1.6
Acidification potential [SO_2 equivalent; AP]	1 : 3.1
Eutrophication potential [PO_4 equivalent; EP]	1 : 4.4
Photo-chemical ozone creation potential [C_2H_4 equivalent; POCP]	1 : 4.3


Glass and natural stone façades

Part 2 – "Façade variants in natural stone and glass: The OpernTurm example"

Part two of the study compares the ecological performance of the actually executed façade (façade variant 1) of the OpernTurm in Frankfurt on the Main with two theoretical façade variants (façade variant 2 and 3):

- Façade variant 1:
  The façade executed on the OpernTurm in Frankfurt, which is made up of back-ventilated natural stone façade elements (17 %), a back-ventilated natural stone façade based on the German standard DIN 18516-3 (33 %) and glass elements (50 %).
- Façade variant 2:
  Back-ventilated natural stone façade based on DIN 18516-3 with a window proportion of 50 %.
- Façade variant 3:
  Glass façade consisting of glass elements (90 %) and back-ventilated natural stone elements conforming to DIN 18516-3 (10 %).

The environmental analysis of the façade variants covered by the study has been carried out on the basis of conjectures regarding methods and data discussed below for a life cycle of the façades of 50 years as stipulated in the *Sustainable Building Guidelines*. Over this period of time, both of the natural stone façade variants exhibited marked ecological advantages regarding all the considered environmental parameters. Depending on the different environmental parameters, the emissions and the energy consumption of natural stone façades are between one and two thirds below those of glass façades.
If the construction phase is considered separately, it becomes apparent that the energy requirements of glass façades are twice those of natural stone façades. Moreover, natural stone façades display further ecological advantages regarding other environmental parameters such as greenhouse gas emissions as well.

In the further course of the façades' life cycle, the environmental impact during the period of use is most significantly influenced by maintenance measures and replacement cycles. Whereas natural stone façades with their relatively durable construction components require only 50 % of the energy resources needed during the production phase, glass façades require 80 %. During the 50 years under consideration, individual construction elements of glass façades are replaced up to three times. The life cycle assessment results for cleaning with water, while important in the context of economic considerations, are environmentally negligible.
When considering the end of the life cycle, it is to be noted that materials used in glass façades such as aluminum and synthetic materials receive environmental credits because channeling them back into the materials cycle avoids energy-intensive primary production.

The examined types of environmental impact of glass façades (GF) are between 60 and 175 % above those of natural stone façades (executed NSF):

Type of Environmental Impact	NSF : GF
Global warming potential [CO_2 equivalent; GWP]	1 : 1.7
Ozone depletion potential [R11; ODP]	1 : 2.8
Acidification potential [SO_2 equivalent; AP]	1 : 1.6
Eutrophication potential [PO_4 equivalent; EP]	1 : 1.6
Photo-chemical ozone creation potential [C_2H_4 equivalent; POCP]	1 : 1.7

The Frankfurt OpernTurm during construction

2 Methods Used

2.1 Life Cycle Assessment

The present study is based on the LCA method (life cycle assessment). Life cycle assessment is a systematic analysis of the environmental impact of products during their entire life cycle ("from the cradle to the grave"). This includes the environmental impact during production, during the period of use and during the disposal of the product and all the related upstream and downstream processes of the different phases (for example the extraction of raw materials or the production of auxiliary and operating supplies).

The study also incorporated the indicators life cycle inventory and life cycle impact assessment, which have also been recognized as criteria for ecological quality by the German Sustainable Building Council. In addition, the choice of included impact categories overlaps with a number of the categories prescribed in prEN 15804, a currently drafted European standard for sustainable construction. The life cycle inventory examines the overall primary energy requirements.

Life Cycle Inventory	
Primary energy, renewable	MJ
Pimary energy, not renewable	MJ
Primary energy, total	MJ

Table 2-1:
LCI indicators

To determine the life cycle impact of the system under examination, the study uses the CML method collection of Leiden University with the characterization factors of 2001.The environmental impact categories human and eco-toxicity were not included as the underlying theoretical models are still being developed and can not yet serve as credible foundations for evaluation. The following LCIA indicators were considered:

Life Cycle Impact Assessment Indicators*	Unit
Global warming potential (GWP)	[kg CO_2 equivalent]
Ozone depletion potential (ODP)	[kr R11 equivalent]
Acidification potential (AP)	[kg SO_2 equivalent]
Eutrophication potential (EP)	[kg PO_4 equivalent]
Photo-chemical ozone creation potential (POCP)	[kg C_2H_4 equivalent]

Table 2-2:
LCIA indicators

*A detailed description of the impact categories can be found in the appendix.

The present life cycle assessment was carried out using the life cycle assessment software GaBI 4 (/GaBI 4 2007/) in accordance with ISO 14044 2006 ff. All datasets relevant to the analysis have been taken from the GaBI 4 database. None of the data used is older than eight years.

2.2 Approach

The life cycle assessment was carried out in three main steps:

- Collection of the data for the manufacturing and use (cleaning and maintenance) of natural stone and glass façades..
- The assumed replacement cycles are based on the average life expectancies from the Sustainable Building Guidelines, which are also used for certification by the German Sustainable Building Council. The selected lifespans are based on conventional estimates and do not preclude that the actual lifespan of individual building materials (e.g. insulation materials, natural stone, aluminum elements) may be longer.
- Computation of the environmental impact of the façade variants over the life cycle of the façade, quality control, evaluation and interpretation of the results.

2.3 Framework of the Study

2.3.1 Unit of Analysis – Part 1

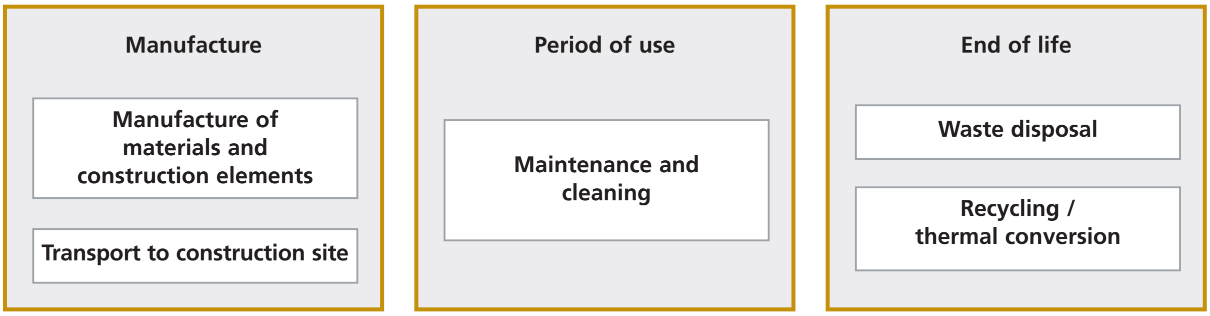
The unit of analysis of part one of the life cycle assessment study is defined as one square meter of a non-load-bearing wall.
This entails that no structural properties such as impact loads, glass statics or the substructures of natural stone façades were considered. The study also does not account for further structural-physical differences of natural stone and glass elements. These include for example light transmission or the heat transfer coefficient (U-value), which latter comes to 0.32 W/m^2K with natural stone and, based on information from the manufacturer, 1.25 W/m^2K with glass façades. On the other hand, glass façade elements yield gains in solar heat. In winter, this has a positive effect on heating needs but can result in increased air-conditioning requirements in the summer.
Additional structural-physical differences such as thermal mass or acoustic and fireproofing-related properties were also not included in the evaluation. Varying thicknesses and their effects on usable space were not taken into consideration either..
The above-mentioned structural-physical properties can only be meaningfully included in an environmental evaluation in the context of examining the performance of a specific building.

2.3.2 Unit of Analysis – Part 2

The unit of analysis of the second part of the environmental life cycle assessment study is the entire façade area of the OpernTurm in Frankfurt, which according to the thermal protection documentation, amounts to 37,020 square meters.
With all three variants, the areas at the corners of the building were defined as back-ventilated areas. These areas amount to ten percent of the entire façade area. The remaining area has been assessed according to the regular elements of the three façade types: back-ventilated façade, glass façade and unitized façade.
The comparative evaluation neither takes account of structural-physical properties (U-values, solar heat gains, thermal mass, etc.) nor of the façades' impact on the resulting gross floor area.

2.3.3 System Boundaries

Environmental life cycle assessment encompasses all life cycle phases "from the cradle to the grave". As the below figure shows, the life cycle is composed of the manufacturing phase, the period of use (not including the energy requirements during use) and the end of life.



Environmental life cycle assessment begins with a consideration of the extraction and manufacturing of the deployed raw and auxiliary materials (natural stone, aluminum, steel, etc.). This includes the processing of raw materials to intermediate and end products (natural stone slabs, windows, etc.) as much as the transport of the construction elements to the building site.
In the first part of the environmental life cycle assessment study, cleaning and maintenance measures are analyzed for a period of 100 years. Given that the second part of the study considers a completed office building, the evaluation period has been set to 50 years in accordance with the German certification for sustainable building requirements.
The cleaning cycles have also been taken from the guidelines of the German Sustainable Building Council (DGNB 2009). For the calculation of maintenance and replacement cycles, the *Sustainable Building Guidelines* of the Federal Ministry of Transport, Building and Urban Development have been used (BBR 2002).
For the end-of-life assessment, the different materials each receive a specific treatment.
Mineral building materials such as concrete and natural stone are reprocessed, mineral rock wool is deposited, metals such as aluminum frames or sheets can be recycled and returned into the materials cycle.

2.3.4 Cut-off Criteria

All components that are relevant to life cycle assessment have been taken into account. Thus only investment goods such as machines and buildings that were used in manufacturing precursors such as natural stone or concrete as well as administrative buildings were not included in the data set as the effects were deemed to be irrelevant.
However, it can not be guaranteed that all the materials used in construction were exhaustively included in the study. To ensure a reasonable relation between input time and effort on the one hand and results on the other, especially the evaluation of large numbers of small parts has been made. As the documents that were submitted have been examined in detail, the study has taken into consideration all construction elements that are essential for the performance of the façade. It can therefore be assumed that all materials that entered the system and that account for more than one percent of its total mass or contribute more than one percent of its total energy requirements have been included in the analysis.
The building materials were modeled using data sets of the GaBi 4 software tool, which were put together according to the DIN 14040 standard.

3 Environmental Life Cycle Assessment – Part 1

Typical Natural Stone and Glass Façades

This section provides a detailed account of one square meter of a back-ventilated natural stone façade and one square meter of a glass façade from a life cycle assessment perspective by considering manufacturing, maintenance and end of life. The analysis covers a period of 100 years.

3.1 System Description of a Typical Natural Stone Façade

3.1.1 Description of a Natural Stone Façade

As can be seen in figure 3-1, the back-ventilated façade consists of a concrete wall lined with thermal insulation panels of mineral wool. Mortar anchorings fasten the natural stone cladding to the concrete. The gap between the insulation panels and the natural stone cladding enables air circulation.

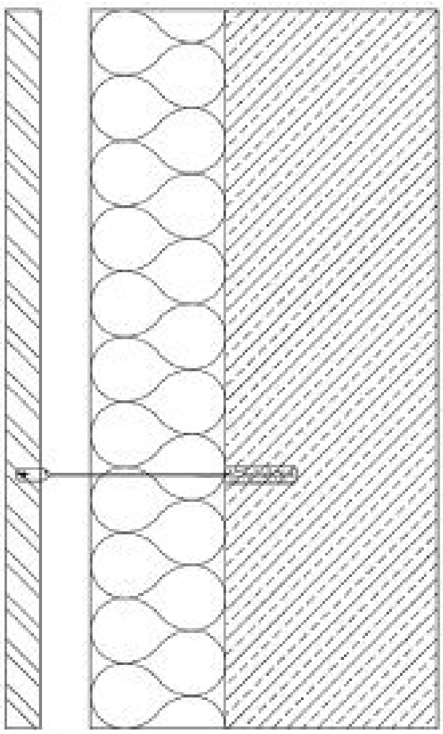
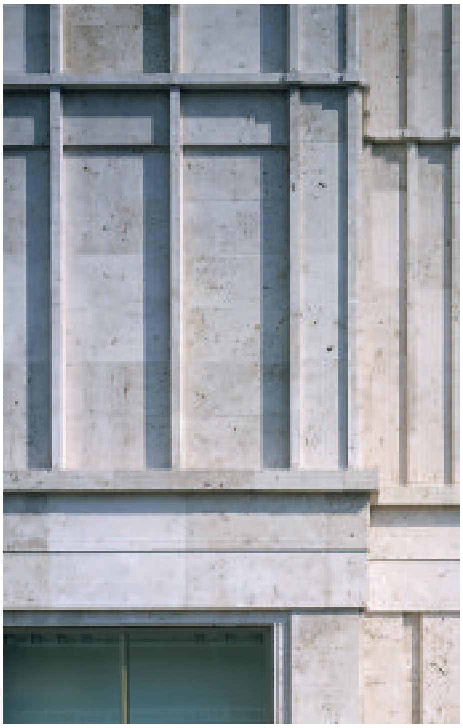


Figure 3-1: Cross-section of a back-ventilated natural stone façade



Back-ventilated natural stone façade

3.1.2 Materials Used

Table 3-1 lists the amounts of materials needed in manufacturing one square meter of natural stone façades.

Natural stone façade – 1 m²					
		Manufacture			
Construction Component / Layers	Materials	Length [m]	Area [m²]	Thickness [m]	Mass [kg]
Load-bearing exterior walls					
Wall	Concrete		1.00	0.20	470.40
Wall	Reinforcement steel		1.00	0.20	31.40
Insulation	Mineral wool		1.00	0.08	3.68
Fastening elements	Steel				1.00
Exterior cladding	Natural stone		1.00	0.04	80.00
	Total				**586.48**

Table 3-1: Bill of quantities and the materials used in the manufacture of the natural stone façade

It can easily be seen that of the materials used in constructing the reinforced steel wall, the concrete accounts for the largest mass portion with 80 %. The reinforced steel contributes 5 %. The insulation amounts to 1 %, and the fastenings to less than 1 %. Natural stone makes up 14 % of the materials used.

3.1.3 The Manufacturing of Natural Stone

The manufacturing of natural stone slabs for construction purposes essentially consists of three steps: the extraction proper in the quarry, the processing of the raw blocks in the stone processing plant and the transport.

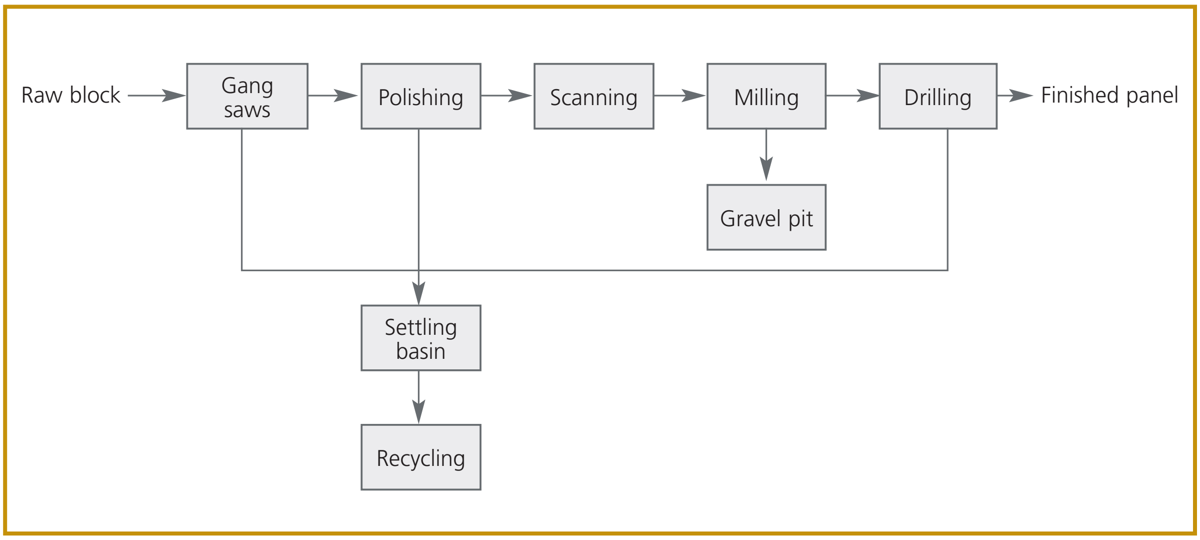
3.1.3.1 Extraction of Raw Blocks in the Quarry

The extraction of raw blocks does not require blasting with explosives. Holes are drilled into the rock at a spacing of 15-20 cm. Then raw blocks of approximately 3.5 m^3 are wedged out of the rock alongside the drilled holes. Wheel loaders transport the blocks within the quarry and load them onto trucks for further transport to the stone processing plant. The data and assumptions the modeled system uses for the processes extraction and transport are presented in table 3-2.

3.1.3.2 Processing of Raw Blocks in the Stone Processing Facility

In the stone processing plant raw blocks are manufactured into finished products – façade panels that are ready to use. On their way to becoming finished panels, raw blocks undergo a number of processes that are depicted in figure 3-2 and that are described in the following.

Figure 3-2: Processing of raw blocks at stone processing plant



First the raw blocks from the quarry are cut with gang saws into panels of a thickness of four centimeters at a speed of 20-40 centimeters per hour. In the ensuing production line, the panels are polished, then scanned for imperfections and flaws, then milled and finally drilled. The waste that results from the processes sawing, polishing, milling and drilling amounts to 25 % of the end product for the considered model. The grain size of the waste varies depending on the process: sawing, polishing and drilling produces mainly stone sludge, whereas milling yields larger-sized fragments. While the coarser waste is processed into gravel (20 % of the overall waste), the stone sludge that has accumulated in the processing water (80 % of the overall waste) is flushed into a settling basin, where the solid parts are separated out by sedimentation.

During the manufacture of natural stone slabs, raw blocks from the quarry are sawed into 4 cm-thick panels

3.1.3.3 Modeling of the Manufacturing Process in GaBi 4

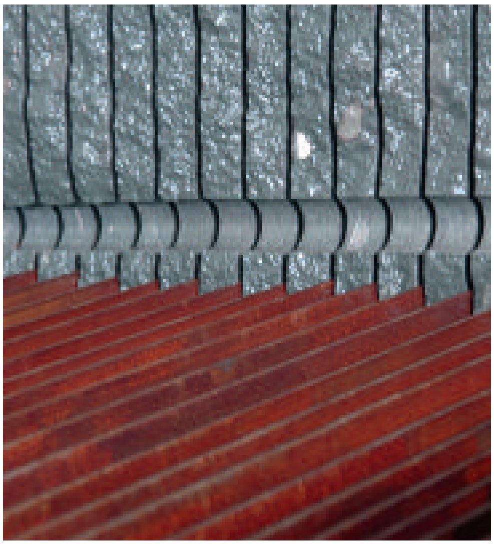
For the extraction of raw stone blocks, the system incorporates the consumption of diesel gasoline for the wheel loaders and of electricity for the constructon machines (drills) used. Subsequently the extracted raw blocks are transported to the stone processing plant at a distance of 200 km with a semi-trailer truck. For the transport, the system assesses diesel consumption and an average load factor of 85 %.

Table 3-2: Natural stone pane: overview of technical assumptions made

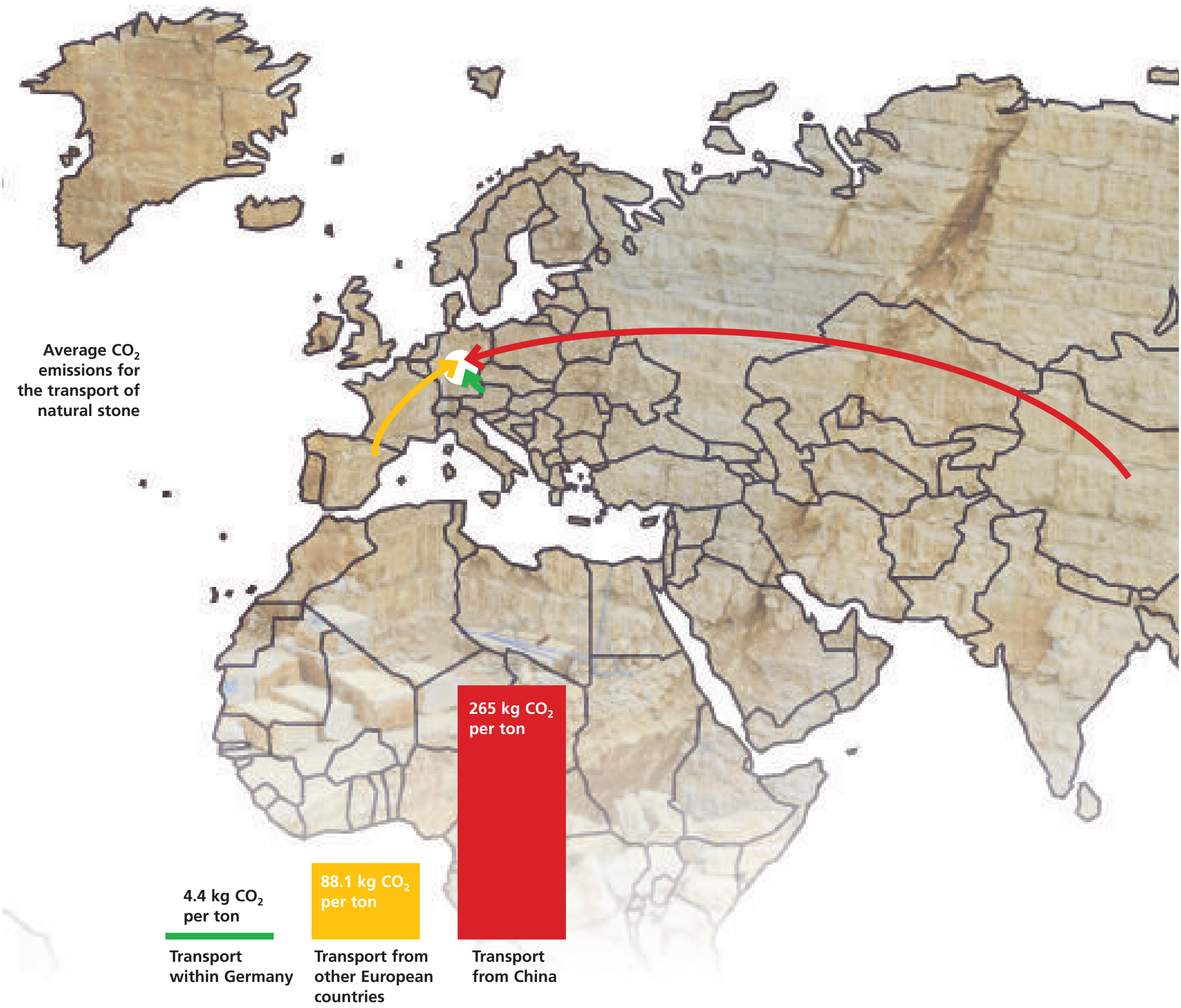
Processes	Data	Data Source
Extraction (quarry)	Diesel consumption: 12.5 l/m³ of raw blocks	GaBi (natural stone modeling)
Transport (extraction – stone processing plant)	Distance: 200 km Vehicle type: semi-trailer truck; 34-40 t maximum allowable weight; Euro 3 load factor: 85 %	Assumption Assumption Assumption (by the trucking company)
Stone processing plant	Electricity requirements: 0.01055 kWh/kg end product Energy mix Germany Waste: 25 % of the end product Percentage of crushed stone (of the waste): 20 % Percentage of stone dust (of the waste): 80 % Water consumption: 0.278 l/kg end product	Stone processing plant GaBi Stone processing plant Stone processing plant Stone processing plant Stone processing plant

The model summarizes the three processes discussed under the process "stone processing plant". If the modeling included only the actual manufacturing processes, energy requirements not related to manufacturing proper such as transporting the stone slates within the processing plant would not be accounted for. The approach chosen in the model however considers the entire energy requirements and apportions them to the manufacturing of the façade panels.

As presented in table 3-2, the accumulated waste is divided into stone sludge and larger fragments of crushed stone at a ratio of 8:2. In the modeling, the accumulated stone sludge is no longer used and treated as construction waste. Occasionally the stone sludge, whose composition resembles the fertile mud of the Nile river, is used as a fertilizer on agricultural land. Utilizing stone sludge in the construction industry is possible, but is not put into practice because of the small amounts and the stone sludge's high content of fine fraction. The coarser waste however is processed into gravel and thus replaces primary gravel. In the system, this is represented as a system extension (credit).



Cutting of blocks with gang saws and processing of the raw panels



3.1.4 The Impact of Transport Distances on the Global Warming Potential of Natural Stone

The environmental impact of the transport of natural stone from the stone processing plant to the construction site is quite significant. This is especially evident when different manufacturing locations are compared. In the following, procuring natural stone and transporting it to a construction site in Frankfurt/Main is assessed in relation to a manufacturing location in China, a manufacturing location in another European country and one within Germany. The transport distances are assumed to be, respectively, 18,600 km, 2,000 km and 100 km. For the German and the European locations, trucks conforming to the European emission standard 3 with a cargo load of 27 tons are assumed to be the means of transport. The calculation of the environmental impact of the transport of natural stone from a production location in China is based on an assumed combination of truck (150 km), train (200 km) and container ship (18,600).

While transporting natural stone from Germany entails a greenhouse potential of 4.4 kg CO_2 equivalents per ton, transport from European countries causes 88.1 kg CO_2 equivalents per ton and thus an approximately twenty-fold amount of greenhouse emissions. With 265 kg CO_2 equivalents, procuring natural stone from China gives rise to 60 times the climatic effects than procurement from Germany.

3.1.5 Natural Stone in the Period of Use

For the period of use, the environmental performance analysis focuses on maintenance (cf. table 3-3). Based on the *Sustainable Building Guidelines*, the study estimates the duration of use for natural stone at 80 years. The assumed duration of use is based on convention and does not preclude a much higher actual lifespan. Premium natural stone façades are usually used for the same period of time as the building in question. According to the *Sustainable Building Guidelines*, the life expectancy of the insulation panels is 30 years and must hence be replaced twice during the 100 year-period under consideration. The study further assumes that the mortar anchorings are also exchanged when the insulation is replaced. During the replacement of the insulation panels, the natural stone is dismantled and then remounted again onto the new insulation layer.

Table 3-3: Bill of quantities for the maintenance phase of natural stone façades

Natural stone façade – 1 m²				
		Maintenance		
Construction Component / Layers	**Materials**	**Cycle [years]**	**Mass [kg]**	**End of life**
Load-bearing exterior walls				
Wall	Concrete	100		Disposal/reprocessing
Wall	Reinforcement steel	100		–
Insulation	Mineral wool	30	11.04	Disposal/reprocessing
Fastening elements	Steel	60	1.00	Recycling
Exterior cladding	Natural stone	80	80.00	Disposal/reprocessing
	Total		**92.04**	

Unlike glass façades, natural stone façades do not require any cleaning. Thus no drinkable water is consumed during the period of use.
For the analysis of the façades' energy efficiency, the decisive value is the heat transfer coefficient, which is also known as U-value. The U-value of the back-ventilated natural stone façade under consideration is 0.32 W/m²K including thermal bridges. By installing a thicker insulation layer, the U-value can be further reduced.

3.1.6 End of Life of Natural Stone

For the most part, at the end of life the materials of natural stone façades are treated in a construction waste processing plant. These materials include concrete and natural stone. After treatment in the processing plant, the materials can be used as gravel substitute, for example for soil stabilization purposes in construction contexts. The mineral wool is deposited at a disposal site for inert materials. The mortar anchorings are recycled and can subsequently be reused.

3.2 System Description of a Typical Glass Façade Element

3.2.1 Description of a Glass Façade Element

Glass façade elements are constructed as mullion-transom systems as schematically depicted in figure 3-3. The façade element consists of thermal protection double glazing filled with argon and is coated using a sputtering process. It contains a protective interlayer and has been fitted into an aluminum frame. The protective interlayer, a polyvinyl butyral foil, prevents splintering in case of glass breakage. The window sealing consists of EPDM seals and polyamide. On the inside, there is a glare shield, and blinds made of polyester fabric are fastened to the aluminum frames. Also on the inside, aluminum profiles of a thickness of 20 cm take on a load-bearing role.

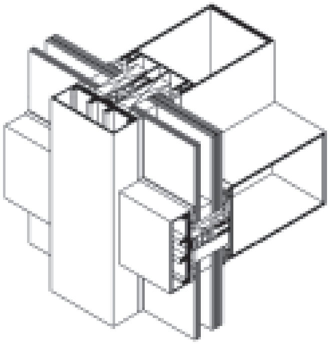
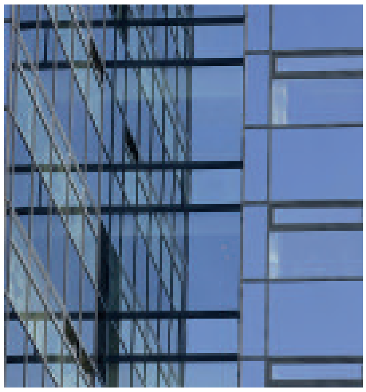


Figure 3-3: Schematic diagram of a glass façade element



3.2.2 Manufacturing of Glass Façades

Table 3-4 presents the materials used in manufacturing one square meter of a glass façade. The study proceeds from the assumption that, always calculated for one square meter, the window frame makes up a proportionate 7 % of the window area. It is also assumed that the window frame is 6 cm wide. From this results a window frame of a length of 1.17 m.

Table 3-4: Bill of quantities and materials for the glass saçade

Glass façade – 1 m²					
		Manufacture			
Construction Component / Layers	**Materials**	**Length [m]**	**Area [m²]**	**Thickness [m]**	**Mass [kg]**
Load-bearing exterior walls					
Substructure	Aluminum	1.17			3.58
Pressure plate	Aluminum	1.17			0.58
Protective Interlayer of the thermal insulation window	Polyvinyl butyral		0.96		0.80
Thermal insulation window	Insulated glazing unit		0.96	0.02	43.20
Sealing	EPDM	1.17			0.50
Sealing	Polyamide	1.17			0.16
Glare shield (on the inside)	Polyester fabric		0.96		1.34
Aluminum frame (Glare shield)	Aluminum	1.17			0.02
	Total				**50.19**

The thermal insulation glass panes make up the largest share of the total mass. The window frames amount to 7 % of the overall materials used.
The modeling of the manufacturing phase is based on the GaBi datasets. For these datasets, the upstream chains were modeled in conformity with the DIN 14040 standard.

3.2.3 The Glass Façade in the Period of Use

Glass façades are cleaned from the outside. According to calculations of the German Sustainable Building Council (DGNB 09), the amount of drinking water used adds up to 1.2 liters per square meter per year. Over the period of 100 years under consideration, the overall consumption of water comes to 120 liters per square meter of glass surface. The materials that are relevant for the maintenance processes over the 100-year period are presented in table 3-5.

Table 3-5: Bill of quantities and materials for the maintenance phase of glass façades

Glass stone façade – 1 m²				
		Maintenance		
Construction Component / Layers	**Materials**	**Cycle [years]**	**Mass [kg]**	**End of life**
Load-bearing exterior walls				
Substructure	Aluminum	50	**3.58**	Recycling
Pressure plate	Aluminum	50	**0.58**	Recycling
Protective interlayer of the thermal insulation window	Polyvinyl butyral	25	**2.41**	Thermal conversion
Thermal insulation window	Insulated glazing unit	25	**129.60**	Disposal / reprocessing
Sealing	EPDM	20	**2.01**	Thermal conversion
Sealing	Polyamide	20	**0.64**	Thermal conversion
Glare shield (on the inside)	Polyester fabric	15	**8.06**	Thermal conversion
Aluminum frame (Glare shield)	Aluminum	15	**0.12**	Recycling
	Total		**147.00**	

As stipulated by the *Sustainable Building Guidelines*, the interior glare shield is exchanged after 15 years. The window sealings need to be replaced after 20 years. Like the protective interlayer, the thermal insulation glazing has a lifespan of 25 years. After 50 years, the aluminum profiles need to be upgraded.
The manufacturers estimate the heat transfer coefficient (U-value) of the glass façade with double-glazing at 1.25 W/m^{2}K.

3.2.4 End of Life of the Glass Façade

Whereas glass bottles are collected in designated containers and recycled, the recycling of window panes faces multiple difficulties:

1. Window glass is a complex material that requires intricate manufacturing processes. Apart from possessing several other qualities, it must be extremely pure and unadulterated by unwanted substances, and its tint needs to be minutely adjustable.
2. Depending on its original use, window glass for a potential recycling might be laminated, printed, enameled, filled with gases, tinted etc. Cleaning glass residue and shards so that they meet the requirements of window glass as specified in point 1 is therefore so complex and costly from a process engineering perspective that it is hardly feasible for economic reasons.

In so far as window glass is recycled, it is ground and melted just like the glass bottles mentioned above, but the recycling cycle is broken as the glass is no longer being used as window glass. Window glass is deposited on a disposal site for inert materials.

Both the sealing and the glare shield possess a calorific value. Because of this, these materials are used for thermal conversion in waste incineration plants.

The aluminum construction components can be recycled and channeled back into the materials cycle. Due to this aluminum recycling, the modeled system includes some recycling potential for glass façades.

Glass façades give rise to cleaning costs of € 1.50 per square meter

3.3 Analysis Part 1 – Typical Natural Stone and Glass Façades

3.3.1 Life Cycle Inventory Analysis

During their life cycle, natural stone façades, with 1743 MJ/m², require significantly less primary energy overall than glass façades with 5854 MJ/m². Both the share of renewable and of non-renewable primary energy consumed is lower than that of glass façades. With natural stone façades, the 4.5 % share of the total energy needs that is supplied by renewable energy is proportionately higher than the relative renewable energy requirements of glass façades.

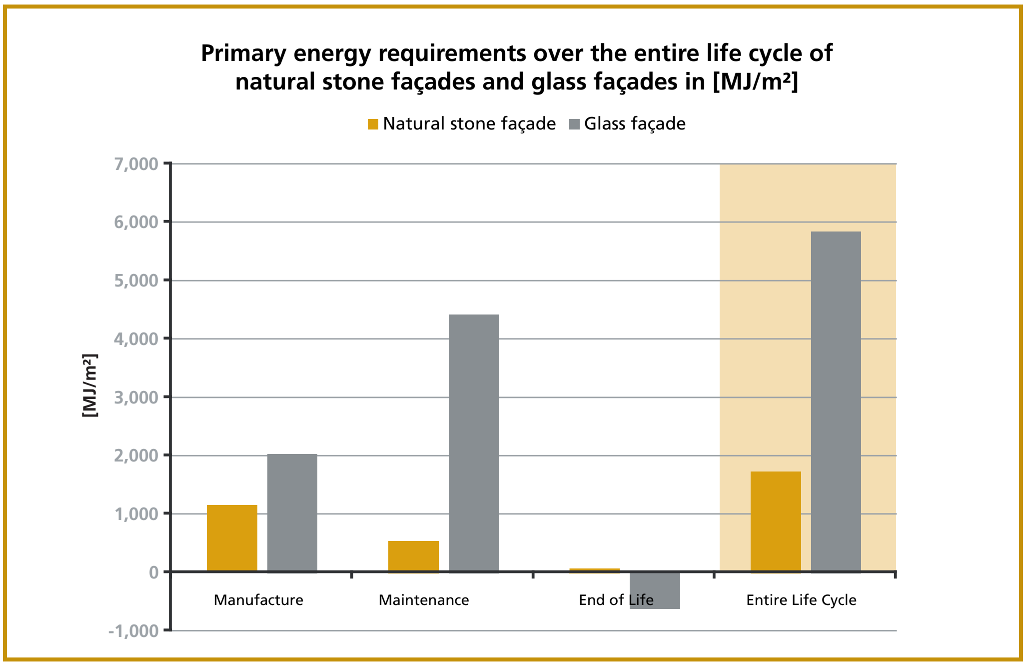
Value	Unit of Measure-ment	Manu-facture	Period of Use			End of Life	Life Cycle
			Cleaning	Mainte-nance	Mainte-nance (EoL)		
Natural Stone Façades							
Primary energy, not renewable	[MJ/m²]	1107.72	0.00	539.11	-15.33	33.11	**1664.61**
Primary energy, renewable	[MJ/m²]	55.88	0.00	27.31	-1.83	-3.08	**78.28**
Primary energy, total	[MJ/m²]	1163.60	0.00	566.42	-17.16	30.02	**1742.89**
Glass Façades							
Primary energy, not renewable	[MJ/m²]	1832.66	0.09	4989.23	-635.55	-448.01	**5738.41**
Primary energy, renewable	[MJ/m²]	206.55	0.00	253.24	-175.07	-169.41	**115.30**
Primary energy, total	[MJ/m²]	2039.21	0.09	5242.47	-810.63	-617.43	**5853.72**

Table 3-6: The primary energy requirements over the entire life cycle of natural stone and glass façades in [MJ/m²].

During the manufacturing phase, with 1164 MJ/m² the overall primary energy requirements of the natural stone façades are lower than those of glass façades. In the phase of use the consumption of drinking water for cleaning the glass façades however is negligible. At the end of life, natural stone façades need 30 MJ/m² primary energy, while glass façades are credited -617 MJ/m² due to their recyclable aluminum elements.

In the maintenance phase the primary energy requirements of the materials used by the two façade variants differs substantially. Because of the frequent replacement cycles of glass façade components, over a period of 100 years glass façades use up more than eight times as much primary energy than natural stone façades. The glare shield on the inside is replaced after 15 years, the window sealing needs to be replaced every 20 years, the thermal insulation glazing as well as the protection layer every 25 years, and the aluminum profiles have to be substituted after 50 years.

Figure 3-3:
Primary energy requirements [MJ/m²]



3.3.2 Life Cycle Impact Assessment

Table 3-7 summarizes the contribution of the different phases of the life cycle to the impact categories under consideration. For both natural stone and glass façades, the impact is analyzed for the manufacturing phase, the period of use and the end of life.

In the manufacturing phase the emissions of natural stone façades are lower for all impact categories than those of glass façades. At the end of life however, glass façades can receive ecological credits for the recycling and reuse of materials that are channeled back into the materials cycle.

In the maintenance phase, which, has been set at 100 years, the glass façade occasions higher emissions in all categories. Mostly this is due to the fact that the thermal insulation glazing needs to be replaced three times during the considered time period. In contrast, the reinforced steel wall of the natural stone façades does not need to be replaced. The natural stone panels are highly durable as well; in terms of figures they are replaced once after 80 years during the 100-year period under consideration. The end of life values of natural stone façades are fairly negligible. Whereas the reprocessing of natural stone and concrete is attended by a low amount of emissions, glass façades receive environmental credits due to their aluminum elements, which allow recycling and reuse in the materials cycle.

Value	Unit of Measurement	Manu-facture	Period of Use				Entire Life Cycle
			Cleaning	Mainte-nance	Mainte-nance (EoL)	End of Life	
Natural Stone Façades							
GWP	[kg CO_2 eq.]	119.65	0.00	37.94	0.61	18.47	**176.66**
ODP	[kg R11 eq.]	6.40E-06	0.00E+00	3.52E-06	7.18E-08	-1.97E-07	**9.80E-06**
AP	[kg SO_2 eq.]	0.2933	0.0000	0.1525	0.0102	0.0542	**0.5102**
EP	[kg PO_4 eq.]	0.0471	0.0000	0.0274	-0.0158	-0.0088	**0.0498**
POCP	[kg ethene eq.]	0.0260	0.0000	0.0090	0.0003	0.0035	**0.0389**
Glass Façades							
GWP	[kg CO_2 eq.]	141.29	0.01	359.87	-19.36	-32.95	**448.85**
ODP	[kg R11 eq.]	6.32E-06	3.10E-10	1.44E-05	-2.99E-06	-2.41 E-06	**1.53E-05**
AP	[kg SO_2 eq.]	0.5794	0.0000	1.3794	-0.1880	-0.1828	**1.5881**
EP	[kg PO_4 eq.]	0.0608	0.0000	0.1729	-0.0060	-0.0065	**0.2212**
POCP	[kg ethene eq.]	0.0537	0.0000	0.1397	-0.0162	-0.0161	**0.1611**

Table 3-7: Results of the life cycle impact assessment during the entire life cycle [per m²]

When the entire life cycle is considered, natural stone façades (NSF) cause significantly lower emissions in all impact categories over against glass façades (GF):

Impact Categories	NSF : GF
Global warming potential [CO_2 equivalent; GWP]	1 : 2.5
Ozone depletion potential [R11 equivalent; ODP]	1 : 1.6
Acidification potential [SO_2 equivalent; AP]	1 : 3.1
Eutrophication potential [PO_4 equivalent; EP]	1 : 4.4
Photo-chemical ozone creation potential [C_2H_4 equivalent; POCP]	1 : 4.3

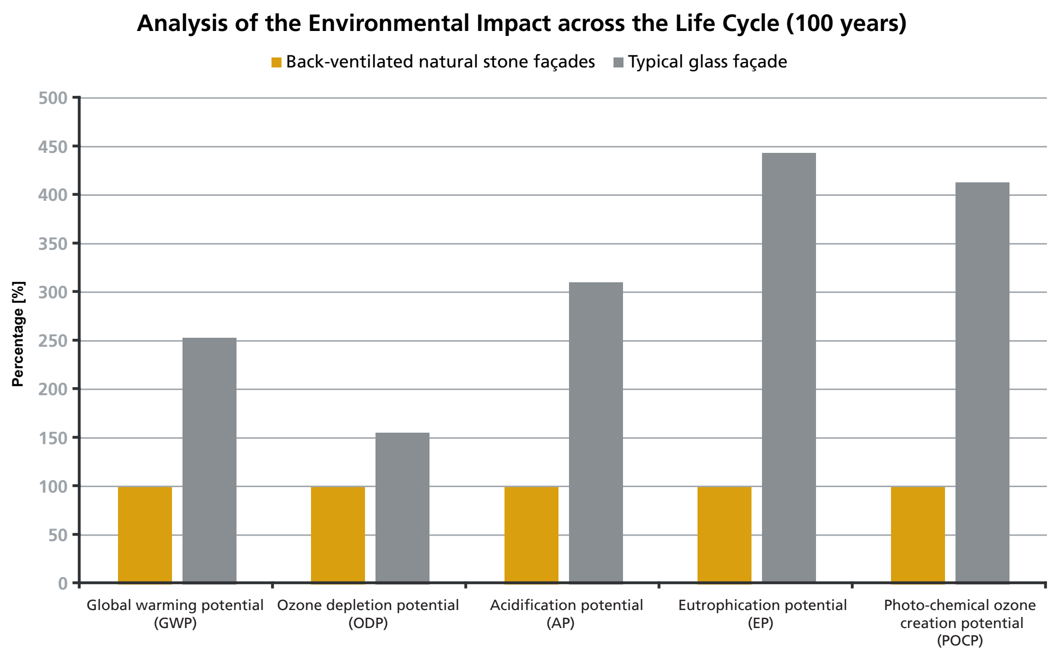


Figure 3-4: Evaluation of the environmental impact

3.3.3 Analysis of the Façade Components over Time

Over the considered period of 100 years, glass façades require a more intensive replacement of materials than natural stone façades. Overall, the mass of the replaced materials with glass façades amounts to 147 kg, while only 92.04 kg of natural stone façades need to be replaced.

In theory, the maintenance of natural stone façades is divided into four phases: after 30 as well as after 60 and 90 years, the insulation is replaced. Before the third replacement of the insulation, after 80 years the natural stone panels are exchanged. The average period of use of the materials has been taken from the *Sustainable Building Guidelines* BBR 2002.

In a realistic situation, the replacement of the insulation and of the natural stone would take place at the same time. In so far as the temporal analysis focuses on a scenario meant to provide an arithmetical determination of the environmental impact, which foregrounds the consumption of materials, the divergent times of replacement do not have any major effect on the results.

Façade variants with glass and natural stone

4 Life Cycle Assessment – Part 2

Façade variants with natural stone and glass: The example of the OpernTurm in Frankfurt

The second part of the study by PE International focused on comparing the actually executed and partially unitized natural stone façade of the Frankfurt OpernTurm with two alternative façades of natural stone and glass.

In the following, "executed natural stone façade" refers to the façade elements used in the construction of the standard floors (floors 7-41) of the OpernTurm. The quantitative analysis of the environmental impact includes this section of the OpernTurm only.
As part 2 of the study is concerned with an office building, the period under consideration is set at 50 years as defined by the German Certification of Sustainable Building.

4.1 Description of the System Unitized Façade

4.1.1 Description of the Executed Natural Stone Façade (17 % unitized, 33 % back-ventilated, 59 % glazing)

The standard element of the natural stone façade of the OpernTurm has a height of 3.57 m and a width of 2.72 m. The parapet and the connecting parts between the window elements have been executed as a unitized natural stone façade. Aluminum ventilation flaps have been installed beside the windows. At the building corners, back-ventilated natural stone façades have been used.
This façade variant thus consists of unitized natural stone (17 %), natural stone façade according to DIN 18516-3 (33 %) and glazing (50 %).

4.1.2 Materials Used

The unitized, back-ventilated façade has been mounted on aluminum profiles, which ensure a fast assembly of the façade during construction. The thermal insulation is attached to the aluminum profiles and consists of mineral wool, which is protected by sheet steel on the inside and aluminum steel on the outside. In turn, the natural stone panels are fastened to horizontal and vertical aluminum profiles mounted onto the aluminum sheets with metal anchorings. The window element is composed of thermal protection double-glazing in an aluminum frame and an inside glare shield. The latter consists of polyester fabric framed by aluminum.

4.1.3 The Manufacturing of a Façade Element with an Outer Layer of Natural Stone

As shown in table 4-1, with 74 % concrete makes up the largest share of the materials used for manufacturing the façade element. With 13 % natural stone, too, amounts to a substantial proportion of the overall materials. The glazing of the thermal protection windows amounts to 7 % of the materials

Table 4-1: Bill of quantities and materials of the natural stone façade (manufacture)

Executed Natural Stone Façade					
		Manufacture			
Construction Component / Layers	**Description / Materials**	**Length [m]**	**Area [m²]**	**Thickness [m]**	**Mass [kg]**
Load-bearing walls					
Back-ventilated façade – wall	Concrete		12.340	0.196	**5.804.845**
Back-ventilated façade – wall	Reinforced concrete		12.340	0.004	**387.483**
Back-ventilated façade – insulation	Mineral wool		12.340	0.080	**45.412**
Back-ventilated façade – connecting elements	Steel				**12.340**
Back-ventilated façade – exterior cladding	Natural stone		12.340	0.040	**987.219**
Unitized façade – wall	Concrete		6.170	0.196	**2.902.423**
Unitized façade – substructure	Aluminum			0.040	**1.011**
Unitized façade – protective layer (interior)	Steel		898	0.002	**10.573**
Unitized façade – insulation	Mineral wool (EIFS))		6.170	0.084	**23.841**
Unitized façade – insulation (every fourth floor)	Mineral wool (EIFS)		123	0.100	**565**
Unitized façade – protective layer (outside)	Aluminum		4.156	0.002	**22.444**
Unitized façade – anchorings	Steel				**6.170**
Unitized façade – exterior cladding	Natural stone		6.170	0.040	**493.609**
Exterior windows and doors					
Window frames	Aluminum	25.973			**26.753**
Thermal insulation windows – seal	Polyvinyl butyral		18.510	0.001	**15.475**
Thermal insulation windows – glass	Insulated glazing unit		18.510	0.018	**832.966**
Sealing	EPDM	25.973			**11.169**
Sealing	Polyamide	33.144	795	0.005	**4.534**
Glare shield (interior) – fabric	Polyester fabric		6.993	0.001	**9.791**
Glare shield (interior) – aluminum frame	Aluminum	18.803			**335**
Windowsill	Natural stone		275	0.070	**38.510**
	Total				**11.831.209**

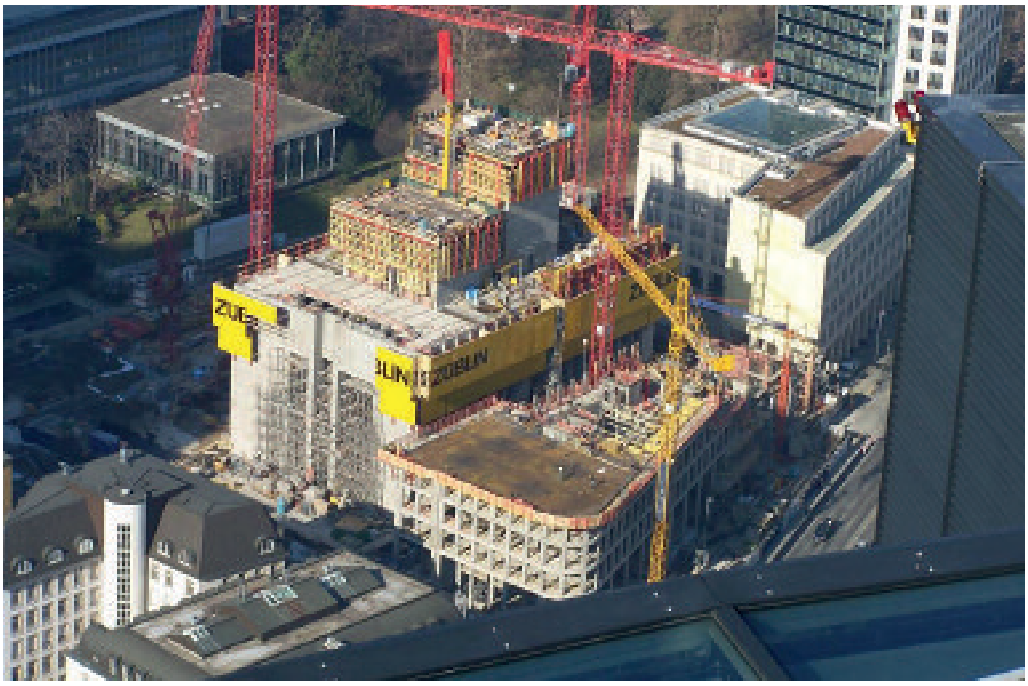
4.1.4 Period of Use

Natural stone does not need to be cleaned at any time during the period of use. The cleaning of the window area requires 1.2 liters of water per square meter (DGNB NBV09), which amounts to l/22.2 m^3 per year.

Table 4-2: Maintenance phase of the executed natural stone façade

Executed Natural Stone Façade					
		Maintenance			
Construction Component / Layers	**Description / Materials**	**Cycle [years]**	**Mass [kg]**	**End of Life / Maintenance**
Load-bearing walls				
Back-ventilated façade – wall	Concrete	100	**0**	Materials for disposal/reprocessing
Back-ventilated façade – wall	Reinforced concrete	100	**0**	–
Back-ventilated façade – insulation	Mineral wool	30	**45.412**	Materials for disposal/reprocessing
Back-ventilated façade – exterior cladding	Natural stone	80	**0**	Materials for disposal/reprocessing
Unitized façade – wall	Concrete	100	**0**	Materials for disposal/reprocessing
Unitized façade – substructure	Aluminum	60	**0**	Recycling
Unitized façade – protective layer (interior)	Steel	30	**10.573**	Recycling
Unitized façade – insulation	Mineral wool (EIFS)	30	**23.841**	Materials for disposal/reprocessing
Unitized façade – insulation (every fourth floor)	Mineral wool (EIFS)	30	**565**	Materials for disposal/reprocessing
Unitized façade – protective layer (outside)	Aluminum	60	**0**	Recycling
Unitized façade – anchorings	Steel	45	**0**	Recycling
Unitized façade – exterior cladding	Natural stone	80	**0**	Materials for disposal/reprocessing
Exterior windows and doors				
Window frames	Aluminum	50	**0**	Recycling
Thermal insulation windows – seal	Polyvinyl butyral	25	**15.475**	Thermal conversion
Thermal insulation windows – glass	Insulated glazing unit	25	**832.966**	Materials for disposal/reprocessing
Sealing	EPDM	20	**22.337**	Thermal conversion
Sealing	Polyamide	20	**9.068**	Thermal conversion
Glare shield (interior) – fabric	Polyester fabric	15	**19.581**	Thermal conversion
Glare shield (interior) – aluminum frame	Aluminum	15	**670**	Recycling
Windowsill	Natural stone	80	**0**	Depositing at waste disposal site
	Total		**980.488**	

The Frankfurt OpernTurm during construction



As part of regular maintenance measures, some of the materials are replaced during the 50-year period under consideration.

As specified by the *Sustainable Building Guidelines* by the Federal Ministry of Transport, Building and Urban Development, the interior glare shield is replaced after 15 years. The window seals only need to be substituted after 20 years. The thermal protection glazing as well as the protection layer have a lifespan of 25 years. The insulation elements are replaced after 30 years. According to the *Sustainable Building Guidelines*, neither the natural stone panels nor the reinforced steel walls need to be replaced during the considered period of time.

4.1.5 End of Life

At the end of life, depending on their type, the materials used are either reprocessed, deposited on a waste disposal site or used for thermal conversion. Given that its reprocessing would be too complex and expensive, thermal protection glazing is deposited, while concrete and natural stone are usually reprocessed.

4.1.6 Transport

For all façade variants, the transport of the raw materials to the plant by truck and of the waste materials to the reprocessing or waste disposal site over a distance of 100 km has been incorporated into the evaluation.

4.2 System Description of the Glass Façade Variant

4.2.1 Description of the Glass Façade (90 % glazing)

The glass façade that is being compared is made up of glass elements (90 %) and back-ventilated natural stone façade elements (10 %).

The concrete areas between the reinforced steel columns and the glass elements are masked with an outside covering. The same applies to the ceilings. This common practice guarantees a unified visual appearance of glass façades. The window elements are 3.9 m long and have a height of 3.1 m. These values have been taken from a specification of a standard glass façade.

The window elements are separated vertically by pane-separating mullions and horizontally by pane-separating transoms. These elements consist of aluminum profiles that also have a load-bearing function within the façade.

4.2.2 Manufacturing of Glass Elements

With back-ventilated façades, at the corners of the building the natural stone panels are fastened with mortar anchorings directly to the reinforced steel wall. Between the natural stone and the reinforced steel there is a mineral wool insulation layer. The glass façade consists of a mullion-transom structure: The covering of the steel columns and ceilings is effected by an insulating cassette, which

Table 4-3: Bill of quantities and materials, description of glass façade elements (during manufacture)

Glass Façade Variant					
		Manufacture			
Construction Component / Layers	**Description / Materials**	**Length [m]**	**Area [m²]**	**Thickness [m]**	**Mass [kg]**
Load-bearing walls					
Back-ventilated façade – wall	Concrete		3.702	0.196	**1.741.454**
Back-ventilated façade – wall	Reinforced concrete		3.702	0.004	**116.245**
Back-ventilated façade – insulation	Mineral wool		3.702	0.080	**13.624**
Back-ventilated façade – connecting elements	Steel		0.000	0.000	**3.702**
Back-ventilated façade – exterior cladding	Natural stone		3.702	0.040	**296.166**
Substructure	Aluminum	21.959			**114.685**
Coverings over ceilings and columns	Steel		8.187	0.002	**164.713**
Coverings over ceilings and columns	Mineral wool		8.187	0.062	**39.895**
Coverings over ceilings and columns	Aluminum		8.187	0.004	**151.074**
Exterior windows and doors					
Pressure plate	Aluminum	37.519			**18.760**
Thermal insulation windows – seal	Polyvinyl butyral		31.067	0.001	**25.972**
Thermal insulation windows – glass	Insulated glazing unit		31.067	0.018	**1.398.036**
Sealing	EPDM	37.519			**16.133**
Sealing	Polyamide		900	0.005	**5.133**
Glare shield (interior) – fabric	Polyester fabric		17.079	0.001	**23.911**
Glare shield (interior) – aluminum frame	Aluminum	37.519			**669**
	Total				**4.130.171**

is protected by a steel sheet and an aluminum sheet. The window elements are comprised of insulation double-glazing with a protective foil of polyvinyl butyral. This foil prevents splintering in case of breakage. The aluminum frames are thermally separated by EPDM and polyamide. On the inside, there is a glare shield made of polyester fabric within an aluminum frame.
Among the materials of the glass façade reinforced steel with 45 % and thermal insulation glazing with 45 % predominate. Natural stone makes up only 7 % of the mass of the materials used. When related to the overall mass, the amount of the remaining materials is of secondary importance (cf. table 4-3).

4.2.3 Use of the Glass Façade Elements

Based on an annual water requirement of 1.2 liters per square meter (DGNB NBV09), the cleaning of the entire window area of the glass façade consumes about 40 m^3 per year. Some materials are replaced in the course of maintenance measures during the considered period of 50 years. As can be seen in table 4-4, the window panes are exchanged once after 25 years according to the Sustainable Building Guidelines of the Federal Ministry of Transport, Building and Urban Planning. The insulation is replaced after 30 years, the sealing after 20 and the interior glare shield after 15 years.

Tabelle 4-4: Bill of quantities, replacement cycles and end of life options during the maintenance period of the glass façade variant

Glass Façade Variant				
		Maintenance		
Construction Component / Layers	Description / Materials	Cycle [years]	Mass [kg]	End of Life / Maintenance
Load-bearing walls				
Back-ventilated façade – wall	Concrete	100	**0**	
Back-ventilated façade – wall	Reinforced concrete	100	**0**	
Back-ventilated façade – insulation	Mineral wool	30	**13.624**	Disposal/Reprocessing
Back-ventilated façade – exterior cladding	Natural stone	80	**0**	
Substructure	Aluminum	50	**0**	
Coverings over ceilings and columns	Steel	30	**164.713**	Recycling
Coverings over ceilings and columns	Mineral wool	30	**39.895**	Disposal/Reprocessing
Coverings over ceilings and columns	Aluminum	30	**151.074**	Recycling
Exterior windows and doors				
Pressure plate	Aluminum	50	**0**	
Thermal insulation windows – seal	Polyvinyl butyral	25	**25.972**	Disposal/Reprocessing
Thermal insulation windows – glass	Insulated glazing unit	25	**1.398.036**	Disposal/Reprocessing
Sealing	EPDM	20	**32.267**	Thermal conversion
Sealing	Polyamide	20	**10.265**	Thermal conversion
Glare shield (interior) – fabric	Polyester fabric	15	**47.822**	Thermal conversion
Glare shield (interior) – aluminum frame	Aluminum	15	**1.337**	Recycling
	Total		**1.885.005**	

Natural stone and glass façades compared

Because of their maintenance cycles of at least 50 years, the aluminum parts and the reinforced steel walls need not be renovated during the given time period.

4.2.4 End of Life

At the end of life, the mineral wool, the insulated glazing unit and the polyvinyl butyral attached to the latter are deposited on a waste disposal site. The metal elements are recycled, and the polyester fabric and the materials that thermally separate the aluminum frames are used for thermal conversion. It becomes apparent that 75 % of the overall materials are deposited and 22 % recycled.

4.3 System Description of the Natural Stone Façade Variant

4.3.1 Description of the Natural Stone Façade Variant (50 % natural stone façade according to DIN 18516-3, 50 % glazing)

This façade variant has the same look as the executed façade with a floor height of 3.57 m and a width of 2.72 m. However, the façade does not contain any unitized areas. This implies that parapets as well as the connecting elements between the windows are realized as back-ventilated natural stone façades. In contrast to the unitized natural stone façades, here the natural stone cladding is fastened directly to the reinforced concrete wall

4.3.2 Materials Used

The mineral wool insulation is placed on the reinforced concrete wall. The natural stone panels are positioned on top of the insulation layer, separated by a gap for air circulation.
The window elements consist of thermal insulation double-glazing with an interior glare shield. The latter consists of an aluminum frame and polyester fabric. Furthermore, aluminum elements are found next to the window elements.

4.3.3 Manufacturing of Natural Stone Façade Elements

As can be seen in table 4-5, reinforced concrete makes up the largest portion of the materials used for manufacturing with 78 %. Natural stone, too, with 13 %, amounts to a considerable share of the mass. The thermal insulation glazing comes to 7 % of the materials used.

Table 4-5: Bill of quantities and materials of the back-ventilated natural stone façade (manufacture)

Natural Stone Façade Variant					
		Manufacture			
Construction Component / Layers	**Description / Materials**	**Length [m]**	**Area [m²]**	**Thickness [m]**	**Mass [kg]**
Load-bearing walls					
Back-ventilated façade – wall	Concrete		18.510	0.196	**8.707.269**
Back-ventilated façade – wall	Reinforced concrete		18.510	0.004	**581.225**
Back-ventilated façade – insulation	Mineral wool		18.510	0.080	**68.118**
Back-ventilated façade – connecting elements	Steel		0.000	0.000	**18.510**
Back-ventilated façade – exterior cladding	Natural stone		18.510	0.040	**1.480.828**
Exterior windows and doors					
Window frames	Aluminum	25.973			**26.753**
Thermal insulation windows – seal	Polyvinyl butyral		18.510	0.001	**15.475**
Thermal insulation windows – glass	Insulated glazing unit		18.510	0.018	**832.966**
Sealing	EPDM	25.973			**11.169**
Sealing	Polyamide	33.144	795	0.005	**4.534**
Glare shield (interior) – fabric	Polyester fabric		6.993	0.001	**9.791**
Glare shield (interior) – aluminum frame	Aluminum	18.803			**335**
Windowsill	Natural stone		275	0.070	**38.510**
	Total				**11.795.481**

4.3.4 Use of the Standard Elements

The natural stone façade does not need to be cleaned at any time during the period of use. Based on an annual water requirement of 1.2 liters per square meter (DNGNB), all in all 22.2 m³ liters of drinking water per year are needed in order to clean the window area. During the 50 years of the considered period, some materials are replaced in the course of maintenance measures.

Table 4-6: Bill of quantities, replacement cycles and end of life options during the maintenance period of back-ventilated natural stone façades

Natural Stone Façade Variant				
		Maintenance		
Construction Component / Layers	Description / Materials	Cycle [years]	Mass [kg]	End of Life / Maintenance
Load-bearing walls				
Back-ventilated façade – wall	Concrete	100	**0**	
Back-ventilated façade – wall	Reinforced concrete	100	**0**	
Back-ventilated façade – insulation	Mineral wool	30	**68.118**	Materials for disposal/reprocessing
Back-ventilated façade – exterior cladding	Natural stone	80	**0**	–
Exterior windows and doors				
Window frames	Aluminum	50	**0**	–
Thermal insulation windows – seal	Polyvinyl butyral	25	**15.475**	Thermal conversion
Thermal insulation windows – glass	Insulated glazing unit	25	**832.966**	Materials for disposal/reprocessing
Sealing	EPDM	20	**22.337**	Thermal conversion
Sealing	Polyamide	20	**9.068**	Thermal conversion
Glare shield (interior) – fabric	Polyester fabric	15	**19.581**	Thermal conversion
Glare shield (interior) – aluminum frame	Aluminum	15	**670**	Recycling
Windowsill	Natural stone	80	**0**	
	Total		**968.215**	

As stipulated by the *Sustainable Building Guidelines* by the Ministry of Transport. Construction and Urban Planning, the interior glare shield is replaced after 15 years. The window seals need to be renewed after 20 years. The thermal insulation glazing as well as the protective foil have a lifespan of 25 years. The insulation is replaced after 30 years. According to the *Sustainable Building Guidelines*, neither the natural stone panels nor the reinforced steel walls need to be renovated during the period under consideration.

4.3.5 End of Life

At the end of life, the materials used in construction are deposited on a waste disposal site, recycled or utilized in thermal conversion. While the thermal insulation glazing needs to be deposited on a waste disposal site because of its overly complex and expensive reprocessing, concrete and natural stone are customarily reprocessed.

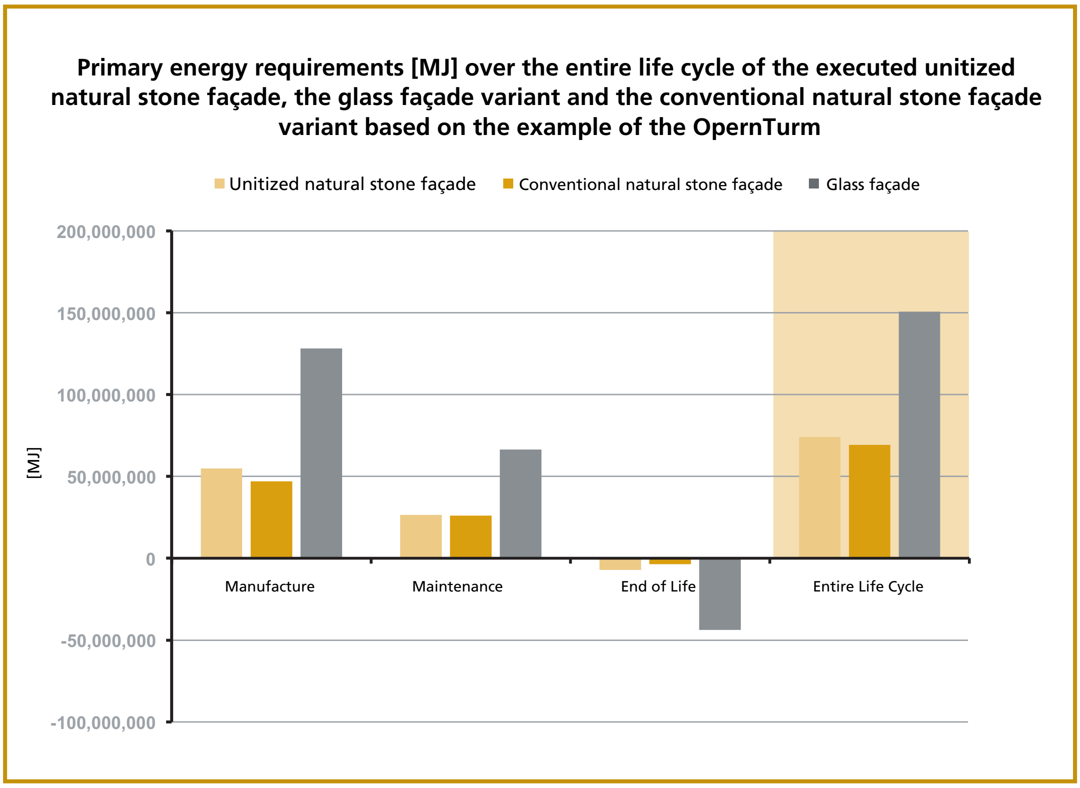
4.4 Analysis – Part 2
Façade Variants of Natural Stone and Glass: The example of the Frankfurt OpernTurm

4.4.1 Life Cycle Inventory Analysis

4.4.1.1 The Overall Primary Energy Requirements of the Façade Variants

Figure 4-1 presents the primary energy requirements of the three façade variants over the entire life cycle. It is easy to see that the primary energy needs of the executed natural stone façade are 50 % lower than those of the examined glass façade variant

Figure 4-1: Primary energy requirements



During the maintenance phase, the durability of the materials of the natural stone façade becomes especially apparent. The primary energy requirements of the glass façade during this phase of the life cycle are about three times as high as that of the natural stone façade. This high energy use reflects in particular the necessary replacement of the glass façade. The ecological credits received by the glass façade at the end of life is for the most part due to the recycling of its aluminum profiles.

		Manu-facture	Period of Use	End of Life/ Manu-facture	Mainte-nance	End of Life/ Mainte-nance	Entire Life Cycle
Executed natural stone façade (17 % unitized, 33 % non-unitized, 50 % windows)							
Primary energy, renewable	[MJ]	51,666,929	839	-5,029,416	27,333,660	-1,287,960	72,684,052
Primary energy, renewable	[MJ]	3,147,188	7	-2,121,051	445,216	-50,690	1,420,670
Glass façade							
Primary energy, not renewable	[MJ]	113,483,177	1,510	-32,243,963	84,666,046	-20,287,661	145,619,109
Primary energy, renewable	[MJ]	14,568,013	12 MJ	-11,607,106	8,331,070	-6,231,313	5,060,676
Natural stone façade (50 % non-unitized, 50 % windows)							
Primary energy, not renewable	[MJ]	45,027,880	839	-2,430,861	26,667,887 MJ	-1,006,500	68,249,245
Primary energy, renewable	[MJ]	1,889,697	7	-1,152,585	363,272	-32,223	1,068,169

Table 4-7: Use of primary energy by natural stone façades and glass façade over the entire life cycle in [MJ]

4.4.1.2 Primary Energy Requirements (Not Renewable) of the Building Materials

In the manufacturing of the executed natural stone façade (17 % unitized, 33 % non-unitized and 50 % windows), the thermal insulation glazing with 33 % of the materials contributes most significantly to energy consumption. With 17 %, the aluminum also adds a considerable portion of the energy use, then follow the reinforcing steel (13 %), the concrete (12 %) and, lastly, the natural stone (10 %). During the maintenance period, it is overwhelmingly the thermal insulation glazing that contributes to the energy needs. At the end of life of the natural stone façade, the recycling of its aluminum elements proves to be advantageous.
With the glass façade (90 % glazing) on the other hand, the primary energy requirements are for the most part determined by the maintenance period. Because of the replacement cycles of the construction components, more primary energy is used during maintenance than during manufacturing if the entire period of 50 years is considered. Here aluminum and glass affect the results most decisively.

4.4.2 Environmental Impact Assessment

The table below summarizes how the energy requirements during the different life cycle phases of the executed natural stone façade and the glass façade contribute to the individual environmental impact categories considered. The impact is assessed for manufacturing, use, end of life, maintenance and maintenance/end of life for the executed natural stone façade, the glass façade and the alternative natural stone façade (table 4-8). This helps to highlight the contributions of the different life cycle phases to the environmental impact categories.
In the categories considered, the environmental impact of the glass façade (GF) is between 60 % and 175 % higher than that of the executed natural stone façade.

Impact Categories	Exec. NSF : GF
Global warming potential [CO_2 equivalent; GWP]	1 : 1.7
Ozone depletion potential [R11; ODP]	1 : 2.8
Acidification potential [SO_2 equivalent; AP]	1 : 1.6
Eutrophication potential [PO_4 equivalent; EP]	1 : 1.6
Photo-chemical ozone creation potential [C_2H_4 equivalent; POCP]	1 : 1.7

Table 4-8: Results for the environmental impact categories over the entire life cycle of the façade variants

Value	Unit of Measurement	Manu-facture	Period of Use	End of Life/ Manu-facture	Mainte-nance	End of Life/ Mainte-nance	Entire Life Cycle
Executed natural stone façade (17 % unitized, 33 % non-unitized, 50 % windows)							
GWP	[kg CO_2 eq.]	4,525,364	59	-61,621	1,951,331	89,575	6,504,707
ODP	[kg R11 eq.]	0.221	2.9E-06	-0.033	0.060	-0.003	0.245
AP	[kg SO_2 eq.]	14,603	0.10	-1,216	7,668	16	21,070
EP	[kg PO_4 eq.]	1,990	0.01	-240	1,090	10	2,849
POCP	[kg ethene eq.]	1,239	0.01	-131	683	6	1,796
Glass façade							
GWP	[kg CO_2 eq.]	8,591,938	107	-2,607,918	6,174,757	-1,440,568	10,718,316
ODP	[kg R11 eq.]	0.551	5.2E-0.6	-0.157	0.359	-0.086	0.678
AP	[kg SO_2 eq.]	31,299	0.17	-13,121	22,686	-7,487	33,378
EP	[kg PO_4 eq.]	3,004	0.02	-565	2,400	-313	4,527
POCP	[kg ethene eq.]	2,810	0.02	-1,212	2,137	-704	3,031
Natural stone façade (50 % non-unitized, 50 % windows)							
GWP	[kg CO_2 eq.]	4,074,466	59	162,148 MJ	1,938,641 MJ	-0.003 MJ	6,264,844
ODP	[kg R11 eq.]	0.182	2.9E-06	-0.020	0.059	-0.003 MJ	0.218
AP	[kg SO_2 eq.]	13,011	0.10	-125	7,636	15	20,537
EP	[kg PO_4 eq.]	1,892	0.01	-196	1,087	10	2,792
POCP	[kg ethene eq.]	1,089	0.01	-31	679	6	1,743

Compared to the executed façade, the non-unitized façade (variant: natural stone façade) would prevent the emission of 230 tons of carbon dioxide equivalents, and over against the glass façade variant, it would prevent the emission of 4,200 tons of carbon dioxide equivalents over a period of 50 years.

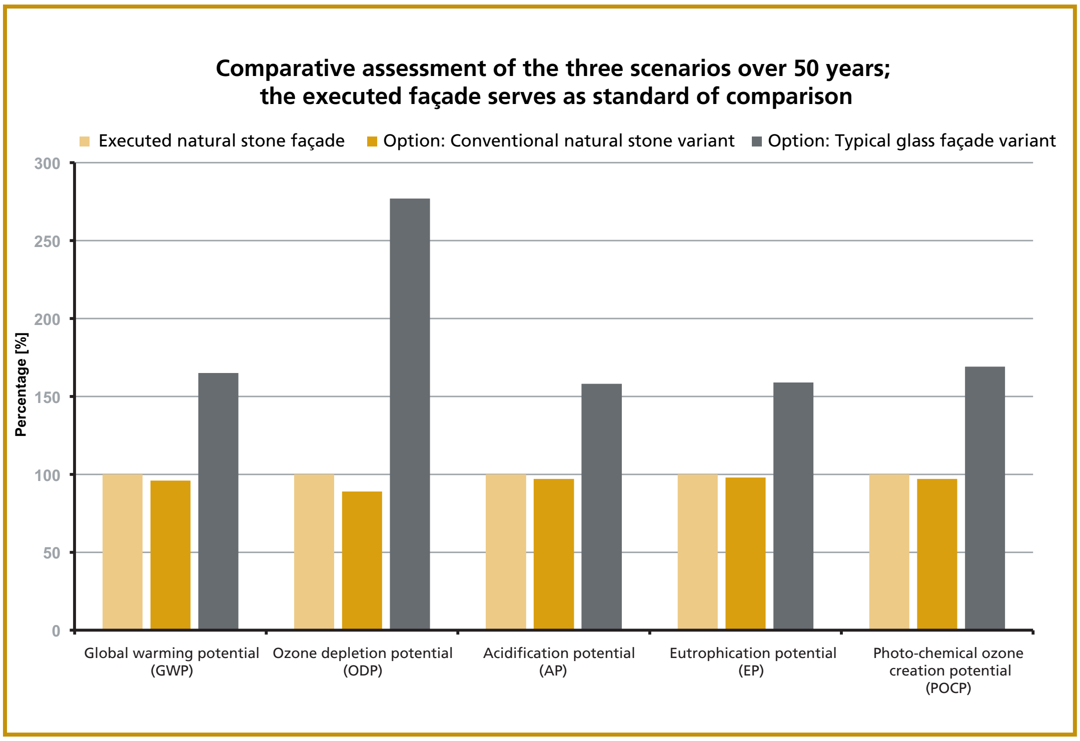
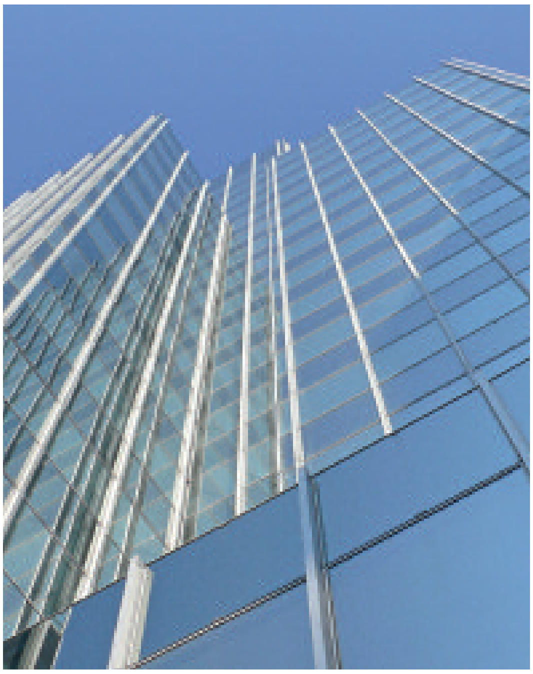


Figure 4-2: Comparative assessment of the environmental impact categories of the three scenarios in reference to the executed façade (100 %)



Natural stone façades prove to be more sustainable than glass façades

5 Economic Considerations

5.1 Guidelines

In cooperation with Drees & Sommer AG, PE International carried out the calculation of the life cycle costs in conformity with the standards laid down by the German Sustainable Building Council (DNGB). The computation of life cycle costs is included in the designated part of the certification process for sustainable buildings that focuses on economic performance.
The guidelines for calculating the life cycle costs can be found under "building-related costs in the life cycle", which is criterion 16 of the DNGB system variant for new constructions of office and administrative buildings (NBV09).
The building-related costs of use are calculated as cash equivalent for the predefined 50-year period to be considered. For the determination of the costs of use, future price increases have been factored in, and for identifying the cash value, the stipulated bank rates and the pre-set 50-year periods have been used.

The calculation in accordance with the cash equivalent method is based on the following assumptions:

General price increases	2 % p.a.
Heating costs	0.09 €/kWh
Electricity costs	0.17 €/kWh
Cleaning of glass surfaces	2.25 €/m²
Cleaning of exterior façade claddings	3.75 €/m²
Cleaning of glare shield (exterior)	2.81 €/m²
Price increases energy costs	4 % p.a.
Maintenance costs	1 % p.a.
Inspection and service costs	0.1 % p.a.
Interest on capital	5.5 % p.a.

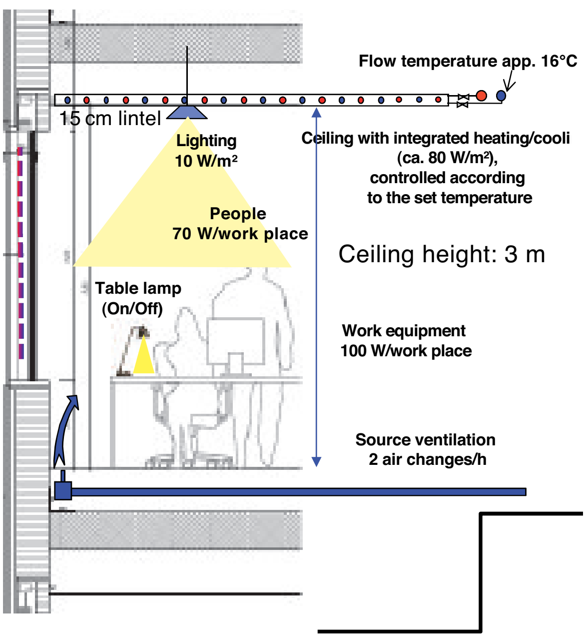
The manufacturing costs of both variants were gathered from a study of the Bavarian audit court (OHR Bericht 2007 TNr. 19). The energy requirements during the period of use were taken from an energy simulation with the software package TRNSYS by Drees & Sommer. The present calculation of life cycle costs is based on the specifications for a natural stone façade and a glass façade with an exterior glare shield included in this simulation. The following façade areas were defined:

	Natural Stone Façade	**Glass Façade**
Window area [m²]	8.4	12.6
Opaque façade area [m²] (including ledges and front)	6.3	2.1

Costs of equipment, the construction site, drinking water supply and waste water disposal, de-installation of parts and the disposal of materials were assumed to be cost-neutral and were thus not integrated into the comparative analysis.

5.2 The Examined Façade Variants

The façade variants considered by this study differ with regard to their glass area (glazing across the entire height of the room as opposed to a façade with parapets of natural stone) and their glare shields (exterior versus interior glare shield).
Both façade variants constitute state-of-the-art systems with interior and exterior glare shields. They require the use of high-grade glazing that meets stringent thermal and optical standards (solar protection glazing with interior glare shield and thermal protection glazing with exterior glare shield).
Differing from the glass façade, the natural stone façade features a parapet that rises to a height of 0.85 m above each floor. The daylight factor of the two façades as defined by the German standard DIN 5034 (daylight in interior rooms) varies only slightly as the daylight factor is measured at a height of 0.85 m.



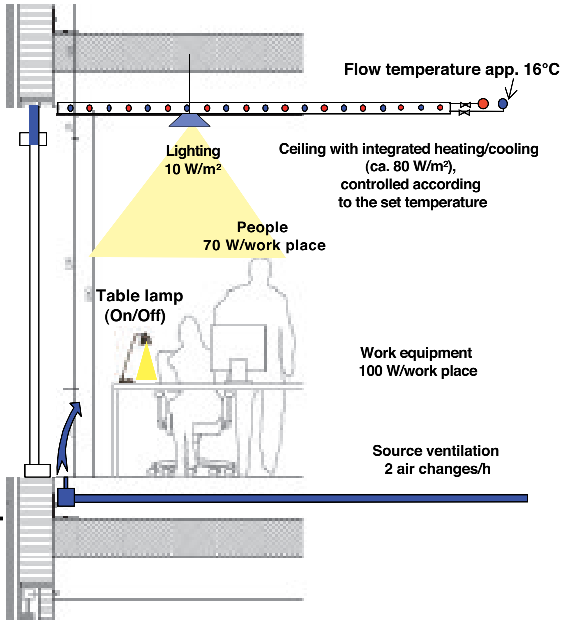


Figure 5-1 (left): Cross section of an office room with a parapet (natural stone façade)

Figure 5-2 (right): Cross section of an office room with a glass façade across the entire height of the room (with opaque glass element instead of a massive ledge)

At the same intensity of use and the same thermal comfort level, the natural stone façade with the 85-cm parapet has only a minimal effect on the energy needed for ventilation (ensuring the necessary air change for reasons of hygiene) and lighting as compared to the glass façade. A consideration of the energy requirements per room shows that the natural stone and the glass façade differ mainly in the areas of heating and cooling.

5.3 Results

If the energy consumption over the entire period of use is considered, the natural stone façade with its window proportion of 50 % exhibits considerable cost savings over against the glass façade. The ultimate energy demand and thus also the energy costs per m^2 net floor area are significantly lower with the natural stone façade. Whereas the natural stone façade gives rise to energy costs of € 10 for each m^2/a, the glass façade is accountable for € 18 per m^2/a, which is 18% more.
The cost advantages of the natural stone façade become even more conspicuous when the the entire life cycle costs in relation to one façade element of a surface area of 14.7 m^2 are considered. With € 37,500, the façade that consists entirely of glass elements causes about 76 % higher costs than the back-ventilated perforated curtain-wall with natural stone cladding.

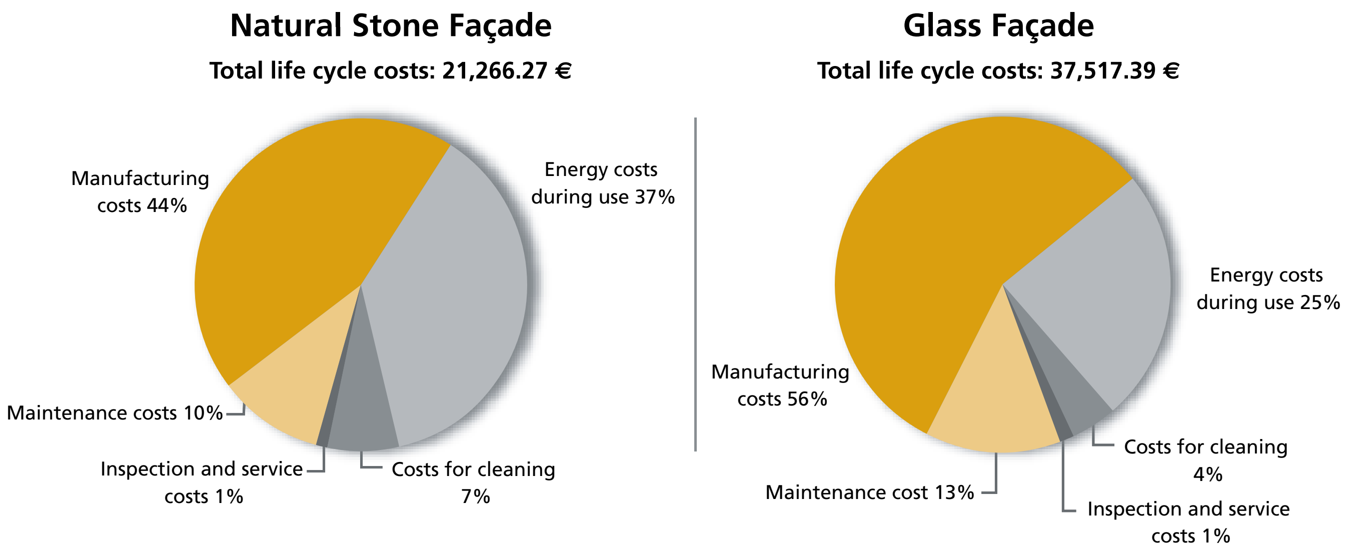


Figure 5-3: Distribution of the life cycle costs in relation to a façade area of 17.4 m² over 50 years

The costs of the natural stone façade are composed of 44% manufacturing costs, 37% energy costs during use and 10 % maintenance costs. Cleaning, servicing and inspections give rise to 8% of the costs.

For the façade made entirely from glass, 56 % of the costs accrue during the manufacturing phase and 25 % result from energy consumption during the period of use. The maintenance costs amount to 13 % and cleaning, servicing and inspection to 5 % of the overall costs.

The difference in costs can for the most part be attributed to the lower manufacturing costs of the natural stone façade, which, at €650, creates only about half the costs per square meter than glass façades at €1,440 per square meter. During the period of use, further advantages of the back-ventilated façade become manifest. If the building is used as office space, its use at the same thermal comfort level results in energy costs that are 16 % more advantageous with the natural stone façade, and so are costs for cleaning, which are 12 % lower.

Table 5-1: Distribution of the life cycle costs in relation to a façade area of 17.4 m²

	Costs Natural Stone Façade [€]	Costs Glass Façade [€]	Difference [€]	Difference [%]
Cash equivalent period of use – energy	7,959.71	9,232.38	1,272.67	16
Cash equivalent period of use – cleaning	1,458.27	1,626.34	168.07	12
Cash equivalent servicing and inspection	223.43	502.71	279.29	125
Cash equivalent maintenance	2,216.87	4,987.96	2,771.09	125
Cash equivalent manufacturing	9,408.00	21,168.00	11,760.00	125
Life cycle costs (total)	**21,266.27**	**37,517.39**	**16,251.11**	**76**

All in all, back-ventilated perforated natural stone façades do not only display ecological advantages, as the environmental life cycle analysis has shown, but they also yield economic benefits.

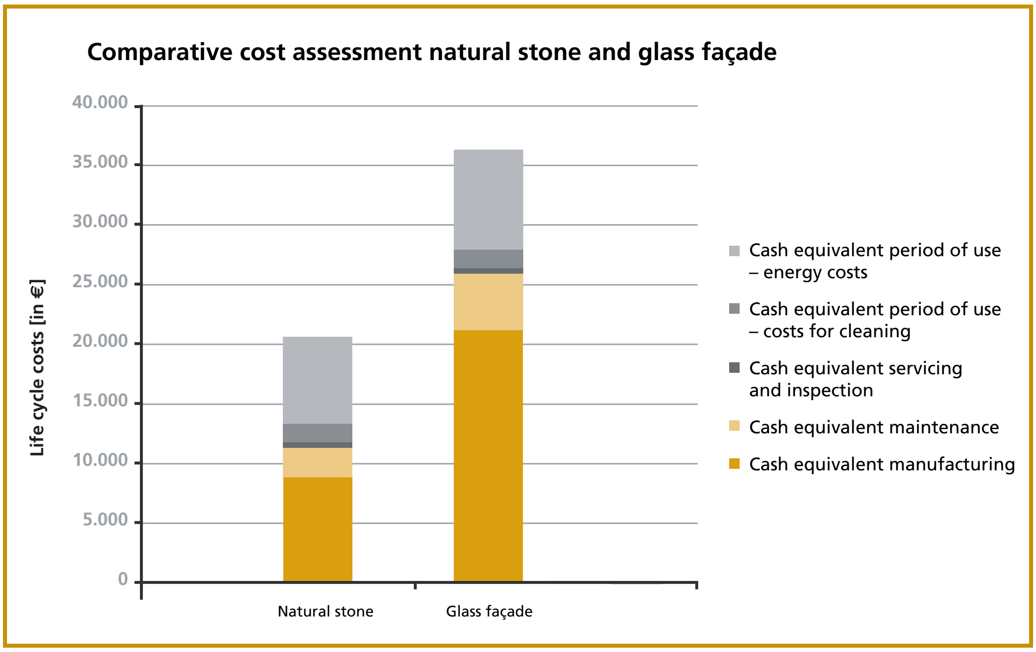


Figure 5-4: Life cycle costs in relation to 14.7 m² façade area with an exterior glare shield (assume energy price increase of 4 %)

5.4 Discussion of the Energy Costs

For the calculation of the energy costs, a price increase of 4 % per year in accordance with the guidelines of the German Sustainable Building Council has been assumed. A study of Germany's Federal Statistical Office (*Energie in Deutschland*, Press Office Wiesbaden 2006) even expects an annual rate of increase of 6 %. If the calculation of the life cycle costs is based on this higher rate of increase, the cost advantage of the natural stone façade turns out to be yet more significant.
The simulation accounts for the heat loss of the façades as well as the solar heat gains of the windows. Windows that can be opened allow for an effective heat dissipation during seasonal transition periods so that active cooling is only necessary during the warmest periods of the summer. The study assumes a typical office use. The actual use of the rooms (computers, fans, preparation of food, etc.) and the occupants' individual regulation of the indoor climate (heating and ventilation patterns, use of the glare shield) have a considerable impact on the energy needs, so that in some cases windows with glass façades use more than 500 kWh/m² of primary energy per year.
In the simulation, the glare shield automatically closes when there is direct radiation, depending on the building's time of use. Furthermore, the calculation of energy needs rested on the premise that the building is equipped with sophisticated building technology. The ceilings feature integrated cooling, which can be controlled individually by room. The possibility of individual regulation decisively affects the energy requirements for cooling. Conventional technological concepts for air conditioning depend on high volume flows of air and thus result in a high energy requirement for moving the air. The differences in the figures for energy efficiency would be yet higher if conventional air-conditioning systems were used.

6 Appendix

Appendix A 1 Primary Energy Requirement

Primary energy requirements may be met by different types of energy sources. The definition of primary energy requirements includes the amount of energy or of an energy carrier not yet been subjected to anthropogenic processing that are taken directly from the hydrosphere, the atmosphere or the geosphere. With fossil energy carriers or uranium, for instance, the energy requirement is expressed as the energy equivalent of the extracted amount of raw materials (i.e. the energy content of the energy raw materials). With renewable energy carriers, the amount of biomass is given an energy value. The amount of hydroelectric energy is based on the change of the potential energy of water (resulting from a difference in altitude). The following aggregated values are used:
The aggregated value **"non-renewable primary energy"**, given in MJ, designates use of the energy carriers natural gas, oil, brown coal, hard coal and uranium. Natural gas and oil are used both for energy generation and as a material in manufacturing, for instance of synthetic materials. For the most part, coal is used for energy generation, while uranium is exclusively used to generate electricity in nuclear power plants.
The aggregate value **"renewable primary energy"**, given in MJ, is usually designated as such and includes wind power, hydropower, solar energy and biomass.
It is in any case essential that the ultimate energy consumption (for example 1 kWh electric power) is not applied against the primary energy used as this would prevent taking account of the efficiency factor of the process of supplying the end energy.
The energy content of the manufactured products is accounted for as energy content of a specific material. It is characterized as the low calorific value of the product, which constitutes its remaining energy content

Appendix A 2 Global Warming Potential (GWP)

As indicated by its name, the workings of the greenhouse effect can be observed on a smaller scale in actual hot- or greenhouses. The same effect is active on a global scale. The incoming short-wave solar radiation hits the surface of the earth and is partially absorbed (which results in direct warming) and partially re-radiated as infrared thermal radiation. The reflected radiation is then absorbed by the so-called greenhouse gases in the troposphere and re-radiated in different directions, so that part of it is again radiated towards the earth, which contributes to further warming.
The greenhouse potential is expressed in carbon dioxide equivalents (CO_2 eq.).
This means that the potential contribution of all emissions is measured in terms of the greenhouse potential of carbon dioxide.

Appendix A 3 Acidification Potential (AP)

For the most part, the acidification of the soil and of bodies of water is caused by the conversion of air pollutants into acids. This causes the pH-value of rain water and fog to drop from 5.6 to 4 or below. Sulfur dioxide and nitric oxide and their acids (H_2SO_4 und HNO_3). contribute significantly to this process. Acidification harms ecosystems, leading to damage such as the dying forest syndrome.
The acidification potential is expressed in sulfur dioxide equivalents (SO_2 eq.).

Appendix A 4 Eutrophication Potential

Eutrophication or nutrient contamination is defined as an excessive enrichment with nutrient at one particular site. The term can refer to aquatic and terrestrial nutrient contamination. Air pollutants, waste water and agricultural fertilizers all contribute to eutrophication.
The eutrophication potential enters the assessment as phosphate equivalent (PO_4 eq.).

Appendix A 5 Photochemical Ozone Creation Potential (POCP)

As opposed to its protective function in the stratosphere, if it is found near the ground, ozone is classified as a harmful trace gas. The photochemical formation of ozone in the troposphere, which is also called summer smog, is suspected to damage plants and materials. Higher concentrations of ozone are toxic to humans.
The environmental assessment gives the photochemical ozone creation potential (POCP) as ethene equivalent (C_2H_4 eq.).

Appendix A 6 Ozone Depletion Potential (ODP)

Ozone originates at high altitudes when oxygen molecules are irradiated by short-wave ultraviolet light. This causes the formation of the so-called ozone layer in the stratosphere (at an altitude of 15-20 km). Through different chemical reactions, about 10 % of the ozone manages to enter the troposphere. Despite its low concentrations, ozone is important for life on earth. Ozone absorbs short-wave ultraviolet radiation and re-radiates it at longer wavelengths in different directions. Only part of this ultraviolet radiation reaches earth. Anthropogenic emissions contribute to a depletion of the ozone layer
For each substance in question, the ozone depletion potential is given as R11 equivalent.

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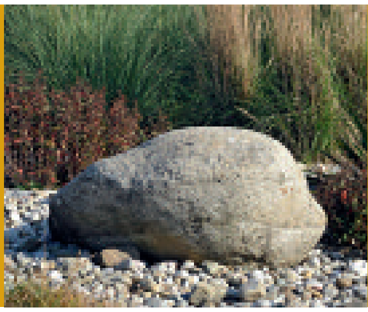

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