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Assessment of Sustainable Construction Measures in Building Refurbishment—Life Cycle Comparison of Conventional and Multi-Active Façade Systems in a Social Housing Complex

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Received: 28 May 2019; Accepted: 14 August 2019; Published: 19 August 2019

Abstract: Building refurbishment plays a key role in the de-carbonization of the European building stock. Whilst the renewal of the thermal envelope increases energy efficiency during the operational phase, the type of material is highly relevant for the overall environmental impact of the refurbishment. Expanded polystyrene (EPS) is most widely used for external thermal insulation systems but is also a material based on fossil resources. Thus, alternatives made from renewable raw materials must be more widely used in order to reach the climate goals. However, comparable data on long-term material effects over the life cycle are needed for developers and planners to make informed decisions. In a Viennese case study for the largest social housing property manager in Europe, two different façade systems have been analyzed to assess the overall environmental impact of the materials. In a comprehensive life cycle assessment, a Multi-Active Façade system based on recycled paper has been compared with a conventional external thermal insulation composite system (ETICS) using EPS. It shows that whilst the evaluation during the operational phase alone results in a similar ecological footprint of the ETICS, the analysis over the whole life cycle provides a clear positive indication for the novel Multi-Active Façade.

Keywords: building refurbishment; thermal insulation materials; life cycle assessment; global warming potential; expanded polystyrene; ETICS; multi-active façade; cellulose insulation board

1. Introduction

In the European Union the renovation rate is currently about 1%, which means that it would take 100 years to renovate the European building stock [1]. With buildings responsible for 40% of energy consumption and contributing to over 36% of CO_2 emissions [2] in Europe, building refurbishment plays one of the key roles in achieving the ambitious climate targets. In Austria the renovation rate is equally low with 1% [3], even though the Austrian Climate Strategies have been citing for years that the rate should be increased to at least 3% and ideally to 5% [4], with the latest Mission2030 Strategy citing an average goal of 2% between 2020 and 2030 [5].

The European Union has set itself the targets to reduce its greenhouse gas emissions to 80% below 1990 levels [6] with a new binding energy efficiency target of 32.5% [2]. In this context the regulatory framework conditions are the Energy Efficiency Directive [7], the Renewable Energy Directive [8] and the Energy Performance of Buildings Directive (EPBD) [9]. In the latest amendment of the EPBD [10], which mainly defines the legislative actions to be taken by the member states related to energy efficiency in buildings, a *long-term renovation strategy* is required in order to decarbonize the building stock by 2050. These legal framework conditions subsequently influence the building regulations and norms on a member state level. In Austria the OIB Guideline No.6 of the Austrian Institute of Construction Engineering [11] is one of the key documents transferring the EPBD into local requirements.

Most of the regulatory framework conditions focus on the energy a building uses during its operation. Thus, energy efficiency in buildings is generally related to heating, cooling, ventilation and power demand. The EPBD with its associated regulations covering the Energy Performance Certificate (EPC) rates buildings based on their primary energy demand and associated CO_2 emissions during its operational phase. Materials and associated emissions related to the production, implementation and discharge are not included in these energy calculations. Considering that buildings consume increasingly less energy during operation due to higher building standards, the energy used over the complete life cycle of buildings becomes ever more important.

Building certification schemes, which provide voluntary structures for building assessments already go beyond the regulatory norms and standards. They include aspects such as land use and water as well as factors related to the materials used in the buildings. Most relevant building certification schemes, such as Leadership in Energy and Environmental Design (LEED) [12], Building Research Establishment Environmental Assessment Method (BREEAM) [13], the German 'German Sustainable Building Council' (DGNB) [14] or the 'Austrian Society for Sustainable Real Estate' (ÖGNI) [15], based on the DGNB or the 'Austrian Sustainable Building Council (ASBC)' (ÖGNB) [16] all provide assessments, which have a particular focus on materials and their use in buildings.

Insulation materials are an important component of energy-efficient construction and thus contribute significantly to achieving climate goals. Polystyrene and other plastic based materials cover together with mineral wool about 90% of the thermal insulation market in Europe [17]. While many natural insulation materials are available on the market for the replacement of mineral wool, hard insulation boards (e.g., polystyrene) have few economically competitive alternatives with equivalent properties from renewable raw materials. Building developers and planners are increasingly aware that the impact of materials is becoming equally important as the energy the materials are saving during the operational phase of the building. For new developments comparable data for insulation materials or whole façade systems are urgently needed for informed decision making processes to select appropriate components based on long-term environmental effects.

For a Viennese case study, a novel façade system called Multi-Active Façade (MAFa) based on recycled paper was implemented. The aim of the case study was the renewable renovation of residential social housing buildings owned by the largest housing property manager in Europe, "Wiener Wohnen". The MAFa system has been chosen mainly due to its environmental friendly characteristics, as it is based on recycled material and integrates passive as well as active solar gains. Another key benefit is the high degree of prefabrication, which reduces the actual construction time on site. In order to provide data for future refurbishment projects, a study has been undertaken to analyze the impact of a conventional façade system in comparison with a novel one. The objective of the study was to compare over the life cycle of the buildings a most commonly used external thermal insulation composite system (ETICS) based on EPS insulation with the novel Multi-Active Façade. The goal was to focus on the material impact of these two different façade system refurbishments in order to assess the long-term environmental effects. As a methodology a Life Cycle Assessment (LCA) with the online-calculator Eco2Soft has been used [18]. A key aspect is to provide a holistic perspective on buildings and their effect on resources and climate over their whole life cycle.

In the next section relevant background and state-of-the-art research related to LCA assessments as well as insulation materials and aspects of refurbishment measures are outlined. Section 3 describes the main principles behind the proposed methodology, followed by the documentation of the case study in Section 4 and the results in Section 5. Finally, the discussion delivers a review of the approach and provides an outlook on how this methodology might be implemented in the future.

2. Background

For energy efficient building refurbishments, the improvement of the outer shell is of utmost importance. In this context external insulation plays a key role to support energy savings during the operational phase of the building. There is a multitude of insulation materials on the market with a wide variety of insulation capacity, application for different uses and inherent material properties.

For exterior parts of the building, blanket insulation or (rigid) foam boards are most commonly used. Blanket insulation consists of flexible fibers, such as fiberglass, mineral wool, plastic or natural fibers. Foam board or rigid foams are very effective in exterior wall sheathing. The most common types of materials for foam boards include polystyrene and polyurethane. Overall glass and rock wool as well as expanded polystyrene (EPS) and extruded polystyrene (XPS) are the main products for building insulation materials. As EPS is based on fossil resources, alternative thermal insulation systems with renewable raw materials are important for the de-carbonization of the building sector. In addition, EPS is also linked to health and safety issues especially concerning fire risks, thus alternative options are increasingly needed [19]. Considering only the energy efficiency in buildings related to the energy use during the operation of the building, the actual thermal conductivity of a material is a key factor. In order to move the building industry from fossil-based materials towards resource efficient alternatives, comparable data on long-term environmental effects are however needed. In this respect a life-cycle analysis, which considers the impact of the material over the whole life cycle of the building (i.e., from sourcing, production, implementation, operation and recycling or degradation) offers a viable way forward.

Classifying properties related to sustainability, the Environmental Product Declaration (EPD) provides a widely accepted framework as an environmental certification Type III characterizing products based on a life cycle approach following the International Standards Organization (ISO) 14025 [20].

Several studies have already highlighted in the past the need to provide adequate data on material-linked emissions and environmental impact. In a comprehensive assessment comparing three commonly used insulation materials based on their life-cycle characteristics, Carabano et al. already stated that the LCA methodology is a globally accepted methodology to assess the impact of materials. This is also acknowledging the fact that there is a need in the building sector to provide such comprehensive classifications of materials to select the most suitable one for a particular project [21]. However, there is also evidence that suggests that different LCA tools provide a variation in results based on different databases related to inventory and impact assessments [22]. In earlier studies LCA analysis was already linked to energy consumption in order to compare the environmental impact of stone wool and polystyrene [23]. Focusing mostly on the global warming potential as well as the embodied energy, Hill et al. provide in their assessment of over sixty environmental product declarations a very broad view on the most commonly used insulation materials [24]. A very comprehensive overview of commonly available materials has been provided by Adity et al., where performance characteristics in terms of thermal conductivity, fire resistance but also life cycle cost and embodied energy were given [25]. Audenaert et al. also argue that the results of a comprehensive life cycle assessment can have a significant impact on the eco-score of the design, stating that the production of the material is in this respect highly influential [26]. In a more recent study by Meex et al. the use of LCA-based environmental impact assessments during the early stages of the building design is also evaluated. The authors conclude, that whilst applying LCA tools within the decision-making process of the architectural design, there are still challenges that need to be overcome for a wider application. Methodological simplification as well as usability of the software tools are cited as potential solutions in this context [27]. Other studies focusing particularly on LCA in refurbishment also confirm that the environmental impact of EPS during the first year after a refurbishment is still higher than the operational energy savings [28].

Whilst the material impact is highly relevant, the architectural integration plays an important factor in the decision for a particular façade system. As ETICS are most frequently used for retrofitting, costs and architectural aspects [29] must be jointly considered in this context. Technological aspects, such as noise protection are additional criteria for the selection of external thermal insulation systems [30]. Several studies related to multi-criteria assessment of advanced insulation materials including aerogels and insulating plaster address a series of aspects in a holistic approach: construction cost, construction time, thermal conductivity, diffusion resistance as well as aspects related to fire safety. With this approach a recent study by Tazikova et al. state that whilst an ETICS system based on EPS boards provides the overall best results [31], this is only valid when long-term environmental effects are excluded. Assessing façade systems and thermal insulation materials for different climate zones, Sierra-Perez et al. conclude, that an ETICS has a better environmental performance in both warmer and colder climate zones than a ventilated façade or a system with internal insulation [32]. In a similar study, where the life-cycle impact of a polyurethane filled composite panel is compared to a composite panel with rockwool, the former achieves better environmental results [33]. Another relevant factor is the degradation of the ETICS. As these systems are exposed to mechanical and climate related damage, the life cycle of the materials used as composite systems must be taken into account when assessing the maintenance and end-of-life aspects [34]. Addressing this aspect from an analytical point of view Ximenes et al. provided numeric indicators for degradation of ETICS based on theoretical and field work [35]. Other studies focus on the financial aspects of ETICS, assessing the economic risks over the life cycle. A recent analysis shows, that degradation factors have highest relevance in the early phases of construction due to high cost of repair and high occurrence rates [36]. The application of building integrated photovoltaic systems (BIPV) is becoming more widely accepted as the efficiency of PV systems is improving. A study by Belussi et al. [37] concludes that the environmental impact of BIPV modules is comparable to conventional PV modules, both in terms of emissions and consumption of resources. Considering however the entire life-cycle, BIPV modules have the inherent advantage that they fulfill a double function by providing both a building skin as well as an active renewable energy system. Other assessments of insulation materials also put a particular focus on the renewable and non-renewable primary energy in the production process [38] as well as additional impact categories such as ozone depletion, terrestrial acidification as well as freshwater and marine eutrophication [39].

Especially for refurbishment projects, the thickness of the added layers is highly relevant. Materials with an extremely low thermal conductivity subsequently need less space in the outer wall. In cases where the thickness is of particular importance (i.e., when the façade must not protrude beyond a certain limit) advanced insulation materials with low thermal conductivity values are required. Vacuum insulation panels (VIPs) can provide a useful alternative to more conventional ETICS with EPS insulation, however particular care must be taken regarding temperature and moisture on the inside of the wall as well as regarding the potentially enhanced effect of thermal bridging [40]. Whilst the energy related impact (e.g., global warming potential) of fossil-based insulation materials can be relatively high compared to non-fossil-based or recycled materials, using bio-based materials has the added benefit of storing carbon in the very same products that also add to the energy efficiency of the buildings. Even though these materials usually require a certain amount of processing and transport, some of the biogenic materials completely capture the carbon stored within one year due to their fast re-growing times [41].

In general the assessment of the overall environmental impact of insulation materials relates to a multitude of factors: The actual energy input in the production of the material, the transport to the site as well as the accumulated energy savings throughout the life-span of the material, which in turn is also dependent on the type of building and building systems, must all be taken into account. Mazor et al. [42] highlights the interaction between these aspects in a study describing the life-cycle perspective of two rigid thermal insulation systems. It must therefore be considered that even materials based on fossil fuel with a high environmental impact during production such as EPS can have a low overall environmental impact compared to other insulation material when assessed over the whole life cycle of the product [43]. Taking into account the accumulated energy savings the insulation material provides over time, the impact during production can become less significant if the energy used during operation is high in relation to the total energy impact. This logic however alters, when buildings become highly efficient and the embodied energy of the materials in the buildings have a higher energy impact than the building during operation.

3. Methodology

A Life Cycle Assessment is a quantitative assessment process where material and energy flows of products, systems or processes are assessed over the entire life cycle, by taking into account all individual life stages. International standards for life cycle assessments are set out in ISO 14040 and ISO 14044. A LCA assessment consists of four phases based on these standards: Goal and scope definition, inventory analysis, impact assessment and interpretation.

Life Cycle Assessment is currently widely known to be the best way for assessing environmental impacts of materials and products (see also [21–28] as noted in the Section 2). Consequently, this study uses LCA for examining the environmental impacts of two different façade systems. The application of an LCA during the design and post-design stage can positively influence decision-making processes. Two different designs were calculated and applied to one building. “Scenario 1 MAFa” is retrofitted with the MAFa system, while for “Scenario 2 ETICS” an external thermal insulation composite system (ETICS) is used.

The LCA was carried out with the online calculator Eco2Soft [18], which is a widely used tool in Austria for the ecological evaluation and calculations of buildings. This software was selected as it is also compatible with the Austrian building certificate “klimaaktiv” (applied by the ÖGNB [16]). The results of the LCA could therefore be used as input parameters for this certification. Other internationally known tools, such as GaBi and SimaPro are of course more widely used in Europe. However, even though they also use the same ecoinvent database they are not compatible with the Austrian building certification. This compatibility and the already positive previous experience of the building owner with this software were the reasons behind the decision to use Eco2Soft.

Life cycle assessments can be created for different variants of possible building renovation approaches and can therefore form a basis for the selection process in terms of ecology and design. Eco2Soft provides the “Oekoindex OI3” which assesses the ecological quality of all materials on the basis of the environmental indicators global warming potential, acidification potential and the need for non-renewable primary energy. The indicator OI3 rates in a range from 0 to 100 points the quality of the building material, the construction or the entire building. The OI3 points are based on the numerical values of the energy certificate. A low HED of a building in the range of 15 kWh/(m^2yr) can be considered excellent, as well as buildings and constructions with less than 15 OI3 points. The eco-parameters of the building materials required for the calculation of the OI3 indicator are provided by the IBO [44] to the software manufacturers and the baubook Internet database. They are also published on the IBO homepage and updated on an ongoing basis. [44].

- Global Warming Potential (GWP100)
- The GWP describes the impact of a trace gas on global warming. The contributions of greenhouse gases are determined for the time horizon of 100 years and are compared in relation to the impact of CO_2. The Global Warming Potential (GWP100) is described in DIN EN 15804, Annex C (EN 15804: 2012 + A1 (October 2013), Annex C) and expressed in kg-CO_2 equivalents.
- The “GWP total” indicator used for the OI3 index considers both the contribution of greenhouse gas emissions to global warming and the quantities of carbon dioxide stored in biomass [45].
- Acidification Potential (AP)
- Acidification is mainly caused by the interaction of nitrogen oxide (NO_x) and sulfur dioxide (SO_2) gases with other components in the air. The associated consequences include the acidification of natural waters and soils, which lead to loss of biodiversity in both ecosystems. For the calculation of the acidification potential, the average “European acidification potentials” are used. The acidification potential is determined in accordance with DIN EN 15804, Annex C [EN 15804: 2012 + A1 (October 2013), Annex C] and expressed in kg-SO_2 equivalents [45].

- Primary Energy Indicator for non-renewable energy resources ($PEI_{n.ren.}$)
- The demand for non-renewable energy resources is calculated based on the total required amount of energy resources necessary to produce a product or service and is referred to as the primary energy content ($PEI_{n.ren}$). The energy related resources are considered in the form of raw energy that did not undergo any technical conversion or transformation and which has not yet been transported. The primary energy content is calculated from the lower calorific value of all energy-containing resources used and expressed in MJ. For the OI3 index, the $PEI_{n.ren.}$, the primary energy content of all non-renewable resources (e.g., oil or coal) used for the production of the material is applied. In doing so, both energy and material resources are taken into account [45].

The OI3 index is based on the three individual indicators (GWP100, AP and PEIn.ren) and it assesses the overall ecological quality of the material or construction. While the OI3 index is a good indicator for measuring resource efficiency and overall ecological impact and AP maps local effects on air quality, soil and water, this paper focuses on the global warming potential (GWP100) and the Primary Energy Indicator for non-renewable energy resources ($PEI_{n.ren.}$). This is due to the fact that the AP is only present in the construction phase of the building but it cannot be included in the operational phase. Since one of the main aspects of the study is to assess both the construction as well as the operational phase, only the GWP100 and PEIn.ren. were included in the results. The material data is derived from the Baubook [18] guideline as well as values verified by independent third parties, which were calculated according to the product category regulations of Bau EPD Company [46] and are based on the background database ecoinvent [47]. The life cycle inventory is based on the IBO-guideline [48] values for construction materials and is accounted for in a cumulative way across all processes from raw material extraction to the end of the production phase (Cradle to Gate, Modules A1 to A3 in accordance with ÖNORM EN 15804). Test certificates for the building physics and building ecology parameters are stored centrally in the life cycle inventory (see Table 1). Following successful completion of baubook quality assurance, the declared products are listed in all target group-specific platforms and can be found on the baubook database [18].

Table 1. Operating live catalog of the live cycle inventory [45].

Construction	Description	Operating Live
Primary Structure	Support structure	100 years
Secondary structure	All construction layers except: windows, ETICS, building sealing/foils, flooring and building services components	50 years
Windows	Glazing, frames, window components	35 years
ETICS (incl. plaster, adhesives, reinforcing fabric etc.)	EPS-F, cork insulation panels, mineral wool plaster base plates, hemp insulation boards, mineral foam board (exterior facades) etc.	35 years
Plaster	Plaster incl. substrates	35 years
Building sealing/foils 25 yrs	Construction foils of rubber (EPDM), PE membranes, PVC waterproofing membranes, other waterproofing except bituminous waterproofing, release foils etc.	25 years
Building sealing/foils 35 yrs	Aluminum bituminous packing, aluminum vapor barrier, bitumen, bituminous paint, bitumen board, areas of application: in particular roof/outer walls in contact to earth	35 years
Floor coverings 50 yrs	Solid wood floors, floating solid parquet flooring, (ceramic) tiles, natural stone, artificial stone	50 years
Floor coverings 25 yrs	Multilayered parquet, linoleum, PVC flooring, polyolefin floor covering based on PE and PU, rubber flooring, rubber pimpled flooring, laminate flooring	25 years
Floor coverings 10 yrs	Cork, corkment, textile floor coverings (polyamide carpet, wool carpet) Screed coating etc.	10 years
Tertiary construction	Technical building equipment	20/50 years
Floor- and wall coating	Screed coating, paints, wall paint, etc.	10 years

The calculation tool Eco2Soft uses a balance border method (reference limits BG0 to BG6, see Table 2), which either enables an overall view of the building (reference limit 6) or a limited view on just the thermal building envelope (BG0). In Austria, reference limits usually range from reference limit BG0 (building envelope) to reference limit BG3. When balance borders from reference limit BG3 to reference limit BG6 are used, the service life times for the individual component layers are taken into account (see Table 1). This implies that not only the construction of the building is considered, but also the required rehabilitation and maintenance cycles of the component layers over the entire service life of the building. The standardized observation period is assumed to be 100 years [48], this period is also applied to the assessment of the case study described in this paper.

Table 2. Reference limits in standards of BG0 to BG6 [45].

Reference Limit	Included Building Components
BG0	Construction of the thermal building envelope, excl. roofing, excl. moisture seals, excl. ventilated facades, incl. false ceilings
BG1	Construction of the thermal building envelope (complete construction), incl. false ceilings
BG2	Incl. BG1, incl. interior walls (excl. door elements)
BG3	Incl. BG2, incl. interior walls (total, excl. door elements), incl. basement components (incl. basement dividing walls, strip or point foundations), incl. unheated buffer rooms (complete structure), excl. open access areas (staircases, arcades, loggias, balconies, etc.)
BG4	Incl. BG3, incl. open access areas
BG5	Incl. BG4, incl. building technology
BG6	Incl. BG5, incl. all outdoor facilities (carport, bicycle parking, etc.), incl. outbuildings

Considering the many influencing factors, a service life prognosis can only be made if the exact condition of the construction is known. Therefore, Baubook [18] offers material-independent default values for the service life, which are based on the component layer function in the building (see **Error! Reference source not found.**).

For the LCA, which includes a complete assessment of the building, the energy demand for the building is of high importance. Consequently for this study energy certificates were calculated for the different renovation strategies with the building-physics software ArchiPHYSIK [49] and the Passive House Planning Package-PHPP [50]. The values from the energy certificates were used to calculate the total energy demand for the next 100 years for each variant.

4. Case Study

In a case study situated in the 14th district of the city of Vienna, the largest social housing property manager in Europe, "Wiener Wohnen", implemented two different façade systems for the refurbishment of two nearly identical residential building blocks. The aim of the study was to compare a standard external thermal insulation composite system (ETICS) with EPS insulation with a novel Multi-Active Façade system with a cellulose insulation board based on recycled paper. The material and environmental aspects of these two systems were evaluated and compared by means of a comprehensive LCA.

In the course of a research project the housing complex with 54 units was to be renovated to a passive house standard by means of the Multi-Active Façade (MAFa), funded under the framework "Building of tomorrow" by the Austrian Research Promotion Agency (FFG) (project number 840645). The results of the analytical part of the project were subsequently comprehensively summarized in a thesis [51]. The novel Multi-active Facade was developed by the University of Natural Resources and Life Sciences, Vienna (BOKU) and the research company alpS in the earlier COMET research project "B02 eNVELOP/MULTIcover—Multifunctional envelop for thermally renovating façades and buildings." The case study buildings are typical for the Viennese post-war social housing blocks built between the 1950s and the 1970s. The city of Vienna, together with its social housing providers, is successively trying to raise the construction standards of these buildings. Key aspects in this context are the refurbishment of the outer shell, the update and/or renewal of the building services systems, the implementation of increased fire safety and the improvement of accessibility. The City of Vienna wanted to have a best practice example to prove the feasibility of the refurbishment of low-quality social housing building stock to passive house standard.

Due to the fact that the chosen residential complex was well suited to investigate various solutions it can serve as an appropriate replication example for other similar housing estates. Furthermore, the building in the south (Building 1) is affected by noise pollution due to the busy road in front of it and is therefore a good case for the application of the MAFa system as the façade offers an increased sound insulation. Figure 1 shows an aerial view of the two buildings.

Figure 1. Aerial view of the case study [52].

Both original buildings showed a relatively poor construction standard as outlined in Table 3. The heating energy demand was with 135 kWh/(m^{2}yr) for Building 1 and 155 kWh/(m^{2}yr) for Building 2 relatively high, compared to buildings based on current regulations with a heating energy demand well below 50 kWh/(m^{2}yr).

Table 3. Building data before refurbishment.

Building characteristics	Building 1	Building 2
Gross floor area (m^2)	2522.12	1891.10
Area/Volume (m^{-1})	0.41	0.47
Window area (m^2)	348.23	105.91
Building mean U-value (kWh/(m2yr))	1.112	1.297
Heating Energy Demand (HED) (kWh/(m^{2}yr))	135.02	154.73

For both buildings a series of refurbishment measures were carried out. These included the thermal insulation of the ground floor in case of an underlying basement, attic slabs and the exchange of the windows with integrated sunscreen. I addition a decentralized heat recovery ventilation unit was added to each flat. The novel Multi-Active Façade (MAFa) was only added to the south façade of Building 1, as direct solar radiation is a prerequisite for the façade to function in its fullest potential. On all other façades of Building 1 as well as on all façades of Building 2 a conventional ETICS façade has been implemented. Thus the "Scenario 2 ETICS" was calculated with an external thermal insulation composite system on all four facades of Building 1 and the "Scenario 1 MAFa" was calculated by applying the MAFa façade on the south side and the ETICS system on the three remaining façades of Building 1. Scenario 1 with the MAFa system in place is the variant that has actually been implemented. In Figure 2 the current status of the refurbishment with the necessary preparatory work already well under way is shown. In the following Sections 4.1 and 4.2 the function, layers and material properties of the two façade systems are explained in detail.

Table 4 summarizes the calculated U-values and g-values of the building shell after refurbishment. It can be seen, that both the ETICS walls applied on the east, west and north side as well as the MAFa applied on the south side of Building 1 have a similarly low U-Value well below the required U-value for walls of 0.35 W/(m²K) as stated in the relevant guidelines [11].

Figure 2. View of the building site May 2019.

Table 4. U-values and g-values of the building shell after refurbishment.

Component	U-Value (W/(m²K))	g-Value (%)
Window	0.821	0.52
Top floor ceiling	0.083	/
Basement ceiling	0.141	/
ETICS wall	0.109	/
MAFa wall	0.139	0.03

4.1. External Thermal Insulation Composite System (ETICS)

The ETICS as chosen for the conventional facades consists of a resol hard-foam panel and an EPS-F panel. This combination is used to minimise the thickness of the insulation layer and to subsequently decrease deep shadowing from windows due to a potentially much thicker wall. The resol hard-foam panel was selected based on its very low thermal conductivity value of λ = 0.022 W/(mK) resulting in a total thickness of 200 mm for the insulation. The reduced depth has no adverse impact on the thermal insulation properties and a U-value of 0.109 W/(m²K) could be achieved, thus meeting the criteria for the passive house standard [50]. See Table 5 and Figure 3 for detailed build-up of the ETICS system.

4.2 Multi-Active-Façade (MAFa)

The Multi-Active Façade has been specifically developed for refurbishment as it is fully prefabricated and thus significantly reduces the application time on site. The façade serves two main purposes: while a passive house standard is achieved by applying it onto the existing outer walls due to its inherent insulation properties, it includes at the same time all required building services needed for achieving this standard (e.g., the ventilation unit). This leads to the added value of no additional construction work inside the individual flats, which is positive for the residents as they are not affected by immission of dust and noise during construction. The prefabricated façade is mounted onto the existing wall with a layer of 6 to 12 cm of glass wool between wooden frames to compensate for a potentially uneven existing facade. The Multi-Active Façade consists of three elements: the carrier plate, the timber frame construction and the glazing. The carrier plate is a 1.9 cm thick MDF (Medium Density Wood Fiber Insulation Board) with 12 cm of glass wool on top for thermal insulation. The timber frame construction is 5.9 cm thick with a 2.9 cm air layer and a 3 cm corrugated board made of a cellulose insulation board (flexCL) from the company Homatherm, produced from recycled paper. See Table 6 and Figure 4 for detailed build-up of the MAFa system and Figure 5 of the schematics and close view of the structure.

Table 5. Component layers of ETICS façade system.

Number	Layer (from inside to outside)	d (cm)	λ (W/mK)	R (m^2K/W)	OI3 ($\Delta Pkt/m^2$)
1	Lime plaster	2.00	0.830	0.02	14
2	Hollow concrete blocks (800 kg/m³)	30.00	0.600	0.50	8
3	Normal plastering mortar GP lime cement (1,800 kg/m³)	2.00	1.050	0.02	11
4	Adhesive mortar	0.50	1.000	0.01	12
5	Austrotherm resolution insulation panel	16.00	0.022	7.27	92
6	Baumit open adhesive filler W	0.50	0.800	0.01	9
7	Sto-polystyrene rigid foam board EPS-F B&W	4.00	0.033	1.21	11
8	Knauf blauband Tünich gypsum thin plaster	0.50	0.700	0.01	4
			R_{si} / R_{se}	0.130 / 0.040	
	Building element	55.500		9.216	158

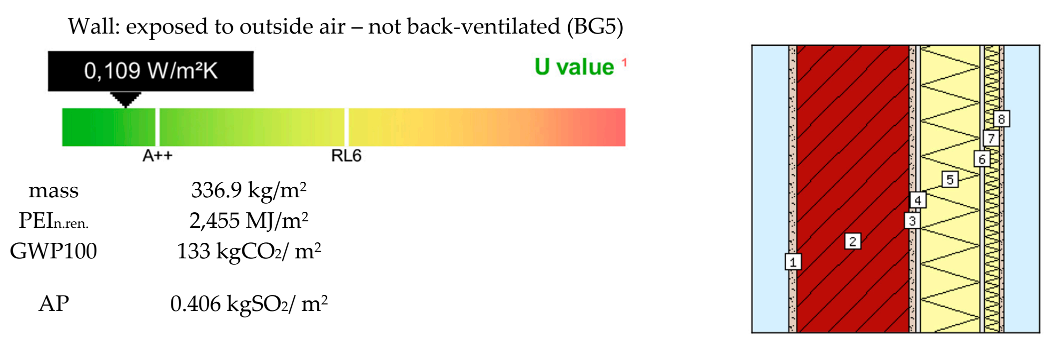


Figure 3. Component layers of ETICS façade system.

Reducing the building's energy demand whilst at the same time integrating renewable energy systems into the building skin are prerequisites for advanced façade refurbishment systems. The MAFa combines both qualities into one system. The reduction of heating energy demand is facilitated by the thermal insulation and the corrugated board, which shows positive effects on the energy demand in winter as well as in summer. The innovative design allows the system to passively gain solar energy during the winter period. As sunbeams are able to penetrate deeply into the construction and thus contribute to passive heat gains, the whole façade can be regarded as a window. According to the Fraunhofer Institute for Solar Energy Systems ISE [53] the g-value of the whole façade has been assessed to be 3% (see Table 4). During the summer, the corrugated board provides shading to the wall because the steep rays of the sun cannot penetrate into the construction. The efficiency of the building is enhanced by the integrated heat recovery ventilation system, which greatly increases the thermal comfort for the residents, as they do not rely on natural ventilation. This is of particular importance for buildings with strong noise immissions, such as the Building 1 from the case study, as it located directly at a road with heavy traffic from a street tramline as well as from cars.

Table 6. Component layers of MAFa façade system.

Number	Layer (from inside to outside)	d (cm)	λ (W/mK)	R (m^2K/W)	OI3 ($\Delta Pkt/m^2$)
1	Lime plaster	2.00	0.830	0.02	14
2	Hollow concrete blocks (800 kg/m^3)	30.00	0.600	0.50	8
3	Normal plastering mortar GP lime cement (1,800 kg/m^3)	2.00	1.050	0.02	11
4	Inhomogeneous (parts vertical)	6.00			
	60 cm (88%) glass wool MW (GW)-W (32 kg/m^3)	6.00	0.035	1.71	14
	8cm (12%) timber (475 kg/m^3 -e.g. spruce/fir)	6.00	0.120	0.50	1
5	Plywood and veneer timber for interior use (800 kg/m^3)	1.90	0.140	0.14	25
6	Inhomogeneous (parts horizontal)	12.00			
	52 cm (87%) glass wool MW(GW)-W (32 kg/m^3)	12.00	0.035	3.43	27
	8 cm (13%) timber (475 kg/m^3 -e.g. spruce/fir)	12.00	0.120	1.00	1
7	Plywood and veneer timber for interior use (800 kg/m^3)	1.60	0.140	0.11	21
8	Plywood and veneer timber for interior use (800 kg/m^3)	1.90	0.140	0.14	25
9	Inhomogeneous (parts horizontal)	5.90			
	130.2 cm (49%) flexCL	3.00	0.041	0.73	5
	130.2 cm (47%) Air (1 kg/m^3)	2.90	0.025	1.16	0
	5.8 cm (4%) timber (425 kg/m^3)	5.90	0.110	0.54	0
10	Glass (2,599 kg/m^3)	0.60	1.000	0.01	50
			R_{si} / R_{se}	0.130 / 0.130	
	Building element	63.90		7.172	203

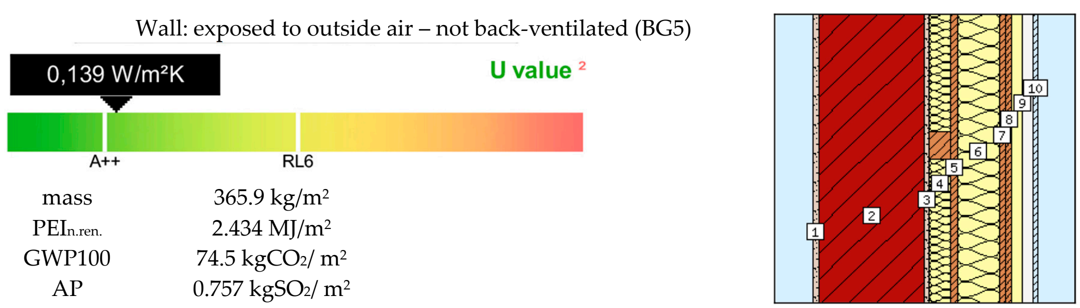
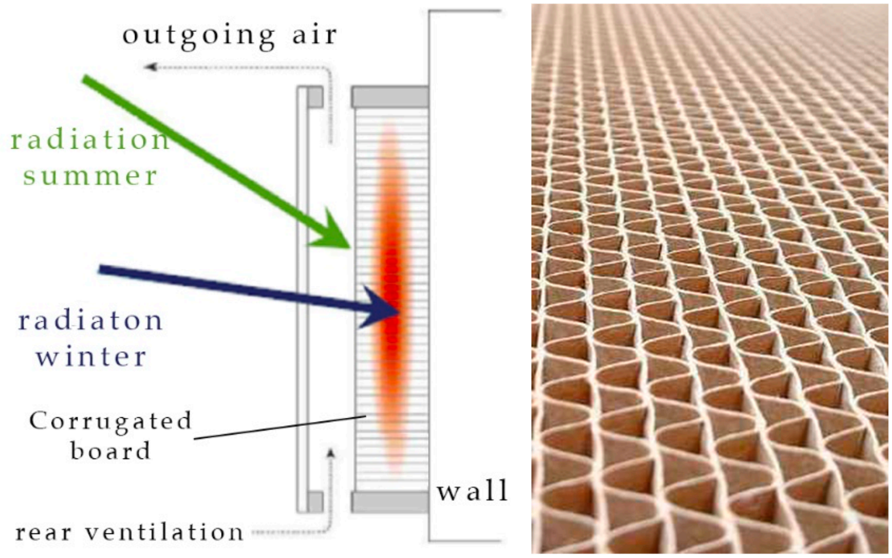


Figure 4. Component layers of MAFa façade system.

The MAFa façade is an active element, implying that it not only reduces the energy demand of a building by means of insulation, but also enhances the overall energy balance by actively producing energy. In order to use the façade as an active element, transparent, frameless glass/glass photovoltaic modules are integrated into the façade to generate energy for the general electricity demand of the housing complex (e.g., lighting for corridors) and for the decentralised ventilation system. The PV system planned for Building 1 has a size of 4.8 kW_P with a yield of about 3285 kWh per year. An energy management system in combination with battery storage ensures operation when there is no solar radiation. The storage system is designed to cover the energy demand for at least 24 h. The Multi-Active Façade was tested with different degrees of transparency with a computational fluid dynamic simulation and also in an experimental laboratory test carried out by the FH Technikum Wien [54] so that the best option regarding passive and active solar yield could be found. The best compromise between active and passive solar use 30% was chosen for the case study.



(**a**) (**b**)

Figure 5. (**a**): Detail of MAFa construction [55]. (**b**): Detailed view of the corrugated board [55].

5. Results

This section describes the results of the LCA assessment detailing the analysis of the material impact and subsequent long-term environmental effects of the two façade systems over the whole life-cycle. The results refer to a 100-year building lifetime, as this is the same lifespan as applied in the GWP100. Also, within the current Viennese building stock, 19.7% buildings were constructed more than 100 years ago and 59.3% of the buildings were constructed before 1970 [56], which highlights that the age of building substance in Vienna roughly corresponds to the average lifespan of 100 years. With regard to the long lifetime of buildings, the reduction of energy needed during the operational phase becomes particularly important. Nevertheless, the used materials have a significant effect on the GWP100 of a building because the lifetime of the individual components is the key factor related to how often the building is refurbished. Consequently, long lasting materials and building components are of utmost importance, as they have a direct positive effect on the GWP100 by reducing overall raw material consumption.

The energy figures from the EPCs related to the building in operation provide the basic energy figures for this study. The data shows that the implemented measures can significantly reduce the energy demand of the building (see Table 7). The mean U-value was reduced from 1.112 to 0.192 W/(m^{2}K) for Scenario 2. For Scenario 1 the mean U-value was reduced to 0.249 W/(m^{2}K). Due to the fact that there was no possibility to insulate the ground floor slab, as the building does not have a basement, the mean U-values for both scenarios are not as low as they could be on a similar building with an insulated floor slab.

Table 7. Building 1 energy demand—before and after refurbishment (based on [51]).

Building characteristics	Unit	Existing Building	Scenario 1 MAFa	Scenario 2 ETICS
Gross floor area	(m^2)	2344	2522	2522
Area/Volume Ratio	(m^{-1})	0.45	0.41	0.41
Window area	(m^2)	348.23	348.23	348.23
Mean U-value	(W/(m^{2}K))	1.112	0.249	0.192
Heating energy demand (HED)	(kWh/(m^{2}yr))	135.02	10.14	10.61
Warm water energy demand	(kWh/(m^{2}yr))	12.78	12.78	12.78
Final energy demand	(kWh/(m^{2}yr))	259.54	79.38	80.65
Primary energy demand (PEI)	(kWh/(m^{2}yr))	313.10	106.19	107.35
Non-renewable primary energy	(kWh/(m^{2}yr))	305.34	95.57	97.00

demand ($PEI_{n.ren}$)				
CO_2 Emissions	(kg/(m²yr))	61.32	19.45	19.74

To ensure that the requirements for the certification for a "Passive House" are met, the energy related calculations were also carried out with the PHPP [50] tool. The calculated heating energy demand from PHPP is 13.0 kWh/(m²yr) (see Table 7), which is lower than the required 15.0 kWh/(m²yr) [57] and the primary energy demand for heating, hot water, utility- and household electricity with a value of 106.19 kWh/(m²yr) also lies below the requirement of 120.0 kWh/(m²yr) [57]. The heating energy demand for Scenario 1 is better than for Scenario 2, despite the mean U-value being slightly higher. This effect is mainly achieved due to the passive solar gains by the MAFa wall. Thus it can be seen that the passive solar gains actually over-compensate the higher U-value of the MAFa wall compared to the ETICS wall. The implemented measures are the basis for preparing an energy-efficient building that is future proof for the next decades. The Austrian building code related to refurbishments currently requires an annual heating energy demand for both buildings of 22.0 kWh/(m²yr). The requirement depends on the area/volume ratio of the building and is defined in the OIB regulative number 6 [11]. After refurbishment, the heating energy demand for Scenario 1 is 53.9% better than required minimum and thus also exceeds by 45.2% the new standard that will come into effect with the new regulations in 2021. Therefore, the refurbished building envelope already fulfills standards coming into force in the future.

In the following Section 5.1 the focus is only on the construction phase and the necessary renewal within 100 years of the Building 1 south facade. Since for this assessment only the façade is calculated, the operational phase is not meaningful and therefore not included. In Section 5.2 the total life cycle of the complete Building 1 is analyzed. The construction phase, the necessary renewal and the operational phase are subsequently all included in the described LCA assessments.

5.1. South Façade—Construction Phase Including the Necessary Renewal Within 100 Years

Examining only the façade constitutes an important step in order to compare the different refurbishment scenarios. For this comparison, the rest of the buildings and the operational phase are not considered, thus only the initial refurbishment and the necessary renewal within the next 100 years are assessed.

From a purely construction-phase point of view the existing wall construction shows best results regarding $PEI_{n.ren.}$ and GWP100, when compared to the refurbished façade. However, this is explained by the simple fact that due to the refurbishment additional material is needed, which consequently has an added environmental impact. Nonetheless, regarding the whole lifetime of a building and thus also taking into account the operational phase of 100 years, the LCA clearly shows that refurbishment positively affects the U-value and the GWP100 (see Table 8). The U-value for both refurbishment solutions is 77.6% better than the U-value for the existing building.

Comparing just the construction of the wall for the south façade highlights the advantages of the MAFa. 54.0 kg CO_2 or 42.2% of the GWP100 per m² can be avoided by using the MAFa wall (see Table 8). Applying the MAFa on the 500 m² south façade has the advantage that 26,750 kg CO_2 emissions can be saved only during the construction compared to the ETICS variant. Regarding the $PEI_{n.ren.}$ both scenarios show nearly identical values with a difference of only 5972 kWh or 1.8%.

Table 8. LCA south façade—construction phase (based on [51]).

Building Component	U-Value	$PEI_{n.ren.}$	GWP100	$PEI_{n.ren.}$ Total	GWP100 Total
	(W/(m²K))	(kWh/m²)	($kgCO_2$/m²)	(kWh)	($kgCO_2$)
Existing wall	1.42	287	32	143,500	16,100
MAFa wall	0.14	676	74	338,056	37,250
ETICS wall	0.11	664	128	332,084	64,000

By extending the analysis from construction phase only to the lifetime of 100 years, the advantage of the MAFa wall is even stronger. The shorter lifetime of 35 years for the ETICS wall in comparison to the 50 years of the MAFa wall has a significant impact on the $PEI_{n.ren.}$ and GWP100. While during the observation period of 100 years, the ETICS wall has to be replaced twice, the MAFa wall only needs to be replaced once because the life time of the construction is 50 years.

In Table 9 the results for the observation period of 100 years is shown. Table 9 also highlights the difference of 117,500 kg CO_2 between the two types. Thus, 38.8% more CO_2 is emitted in case of application of the ETICS façade. The resource consumption for the ETICS façade is significantly higher because the individual components of the construction are not yet suitable for reuse, which results in most of the RESOL foam currently being burned or stored in landfills [58].

Table 9. LCA south façade—construction phase including the necessary renewal within 100 years (based on [51]).

Building Component	U-Value	$PEI_{n.ren}$	GWP100	$PEI_{n.ren}$ Total	GWP100 Total
	(W/(m²K))	(kWh/m²)	(kgCO₂/m²)	(kWh)	(kgCO₂)
MAFa wall	0.14	1352	149	676,112	74,500
ETICS wall	0.11	1993	384	996,251	192,000
Difference-ETICS-MAFa				320,139	117,500

5.2 Complete Building 1—Total Life Cycle

In addition to the construction phase the operational phase plays an important role in the result of any LCA. Especially if the building envelope quality is low, the emissions caused by heating and hot water demand greatly exceed the emissions of the construction phase of the building envelope. Therefore, this chapter includes the primary energy demand for the operational phase in the LCA. In this context the energy generated by the photovoltaic modules of the MAFa is also considered. The 4.8 kW_P PV system produces 3285 kWh per year (1.23 kWh/(m²yr)) of renewable energy.

The following analysis focuses (unlike the results shown in Section 5.1) not only on the south façade, but on the building as a whole. The numbers for the total building are equally relevant as the numbers per square meters, as it is important to understand, how much energy and resources are needed for just one rather small building. Therefore, in the following tables both the results per m² as well as the total figure are listed.

Table 10; Table 11 show the results of the LCA for Building 1. In the first column, the U-values are shown. The second column lists the results per m² followed by the total for the entire building for the construction phase only. The fourth column (operational phase) displays the results of the 100-year usage phase. In the last column (total life cycle) the total values for the construction- and operational phase are displayed for the complete Building 1 with a gross floor area of 2522 m².

Table 10. Total life cycle Building 1-$PEI_{n.ren.}$ (based on [51]).

Scenario	U-Value	Construction Phase		Operational Phase	Total Life Cycle
		$PEI_{n.ren}$	$PEI_{n.ren}$	$PEI_{n.ren}$	$PEI_{n.ren}$
	(W/(m²K))	(kWh/m²)	(kWh)	(kWh)	(kWh)
Existing building	1.42	647	1,631,812	77,010,412	78,642,224
Scenario 1 MAFa	0.14	2016	5,084,594	24,103,901	29,188,495
Scenario 2 ETICS	0.11	3537	8,920,738	24,464,564	33,385,302
Difference Exiting building—Scenario 1 MAFa		−1369	−3,452,782	52,906,511	49,453,729
Difference Scenario 2 ETICS—Scenario 1 MAFa		1521	3,836,145	360,663	4,196,808

Table 11. Total life cycle Building 1—GWP100 (based on [51]).

Scenario	U-Value	Construction Phase		Operational Phase	Total Life Cycle
		GWP100	GWP100	GWP100	GWP100
	(W/(m²K))	(kgCO₂/m²)	(kgCO₂)	(kgCO₂)	(kgCO₂)
Existing building	1.42	177	446,415	15,614,213	16,060,628
Scenario 1 MAFa	0.14	468	1,180,352	4,729,247	5,909,600
Scenario 2 ETICS	0.11	868	2,188,948	4,976,708	7,165,656
Difference Exiting building—Scenario 1 MAFa		−291	−733,937	10,884,965	10,151,029
Difference Scenario 2 ETICS—Scenario 1 MAFa		400	1,008,596	247,460	1,256,056

In the construction phase the difference in the production of the components regarding the $PEI_{n.ren.}$ between the two facades is low. When comparing the two scenarios from a material perspective, meaning that lifetime and the differing necessary renewal of the scenarios are not taken into account, the GWP100 with a difference of 41.8% is in favor of the MAFa wall (Table 11). This stems from the fact that the material used for ETICS is non-renewable, whereas the material used for MAFa comes from renewable sources.

Extending the view from the material perspective to the life time of the components, the difference becomes even more evident. Due to the shorter life time of 35 years, the ETICS wall needs to be replaced twice in the time span of 100 years, whereas the MAFa wall just needs to be replaced once because the life time of the construction is 50 years. This adds up to a total of 8920 MWh for the ETICS variant and 5084 MWh for the MAFa variant, implying that 43.0% more $PEI_{n.ren.}$ is needed if the ETICS variant is chosen. Also, emissions with 2189 tCO_2 are significantly higher in the ETICS variant, which is 46.1% more in comparison to the MAFa variant. In Figure 6; Figure 7 the jumps in the linear lines represent the necessary renewal after 35 and 70 years for the ETICS system and after 50 years for the MAFa system.

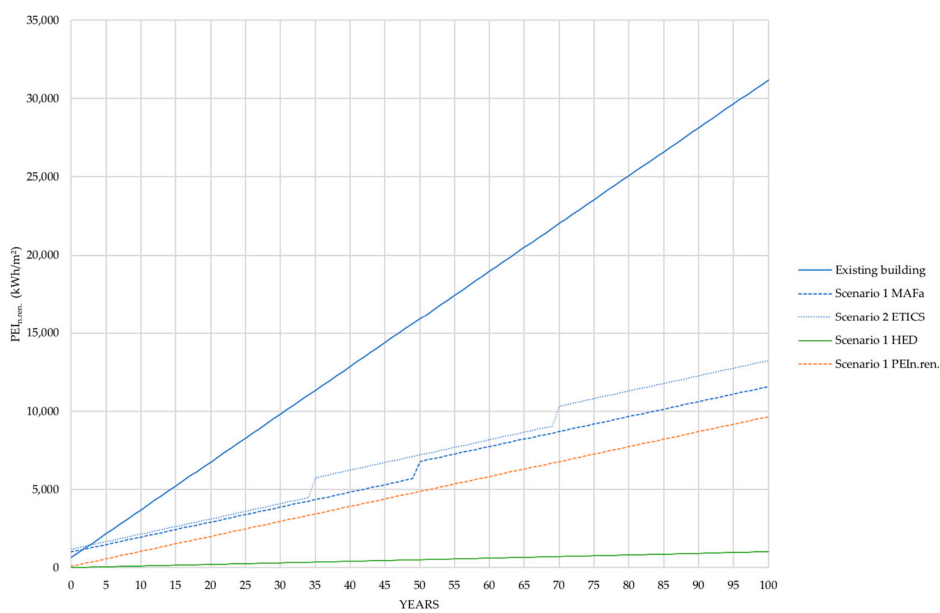


Figure 6. Building 1 total life cycle $PEI_{n.ren}$–comparison of different scenarios.

Assessing the values for the operational phase**,** it becomes clear that this phase has an important environmental impact, which is bigger than for the construction phase. Comparing the two refurbishment variants to the existing building, both $PEI_{n.ren.}$ and GWP100 of the operational phase are in each variant significantly lower. For the MAFa wall the $PEI_{n.ren.}$ is 31.3% and the GWP100 30.3% of the existing variant. For the ETICS wall the $PEI_{n.ren.}$ is 31.8% and the GWP100 is 31.9% of the existing variant. The amount of $PEI_{n.ren.}$ per square meter generated during the production of the MAFa wall can already be saved after 6.5 years during the operational phase (see **Error! Reference source not found.**) and the CO_2 emissions per square meter are balanced after 6.7 years, when the MAFa wall is compared to the existing building (see **Error! Reference source not found.**).

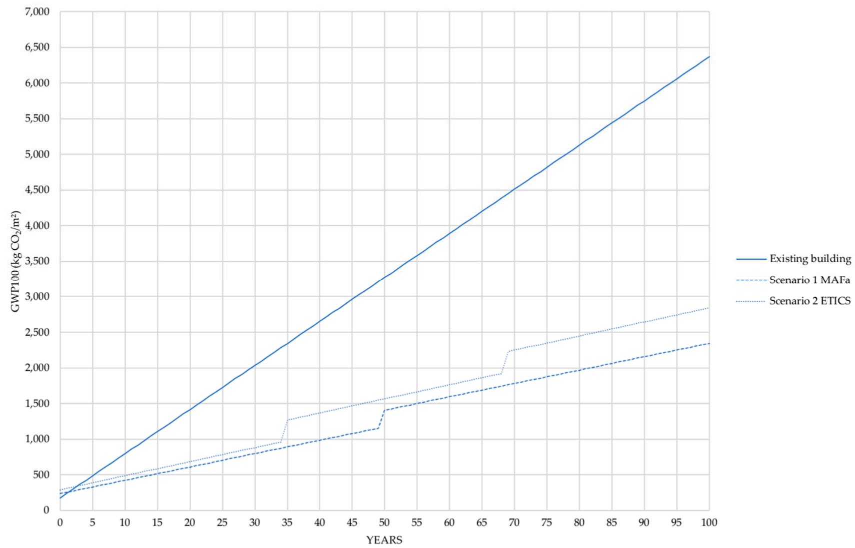


Figure 7. Building 1 total life cycle GWP10—comparison of different scenarios.

The measures applied result in a significant reduction of the energy demand and emissions. It also shows that retrofitting the building envelope provides just one step in reducing the overall energy demand (compare data line "Scenario 1 HED" and data line "Scenario 1 $PEI_{n.ren.}$" in **Error! Reference source not found.**). Because household electricity demand and warm water energy demand are not affected in the same way by the refurbishment as the heating energy demand (which is −92.0% for the MAFa scenario in Building 1 compared to the existing scenario), generating renewable energy on site is the only way to reduce the total energy demand of non-renewable energy. The MAFa wall has PV-modules included, however, the building shape, the vertical arrangement and the limited usable façade surface narrow the size of the PV system. In addition, the roof of the building has already been prepared for the implementation of another PV-system at a later time. The energy generated by the PV is currently enough for operating the ventilation system and to power the lighting in the general areas of the building.

The complete LCA for the total life cycle of Building 1 shows that a significant amount of non-renewable energy and emissions can be saved when a building is refurbished. In comparison to the existing building the MAFa variant saves about 49,453 MWh and subsequently 10,151 t CO_2. With this accumulatively saved energy 52 apartments ($PEI_{n.ren}$ = 95.57 kWh/(m²yr)) with 100 m² each could be supplied for 100 years with their $PEI_{n.ren.}$ demand for heating, warm water and electricity (see Table 12). Looking at the GWP100, 52 apartments (CO_2 = 19.45 $kgCO_2$/(m²yr)) emit about the same amount of CO_2 in 100 years. When the MAFa variant is compared to the ETICS variant, 4 apartments could be supplied with $PEI_{n.ren.}$ and 6 apartments would consume the same amount of CO_2 (see Table 13).

Table 12. Total life cycle—comparison MAFa with existing wall and ETICS $PEI_{n.ren}$ (based on [51]).

Compared Scenarios	Difference $PEI_{n.ren}$ (kWh/(m²yr))	Difference $PEI_{n.ren}$ (kWh/yr)	Difference $PEI_{n.ren}$ (kWh)
Scenario 1 MAFa—Existing building	196	494,537	49,453,729
Scenario 1 MAFa—Scenario 2 ETICS	17	41,968	4,196,808

Table 13. Total life cycle—comparison MAFa with existing wall and ETICS GWP100 (based on [51]).

Compared Scenarios	Difference GWP100 ($kgCO_2/(m^2yr)$)	Difference GWP100 ($kgCO_2/yr$)	Difference GWP100 ($kgCO_2$)
Scenario 1 MAFa—Existing building	40	101,510	10,151,029
Scenario 1 MAFa—Scenario 2 ETICS	5	12,561	1,256,056

Given the fact that the thermal properties of the two scenarios are very similar, the results related to energy efficiency are almost equal. However, the environmental impact of the construction phase becomes more evident when comparing the percentages of the construction versus the operational phase as shown in **Error! Reference source not found.** for the primary energy indicator ($PEI_{n.ren}$) and in **Error! Reference source not found.** for the global warming potential (GWP100).

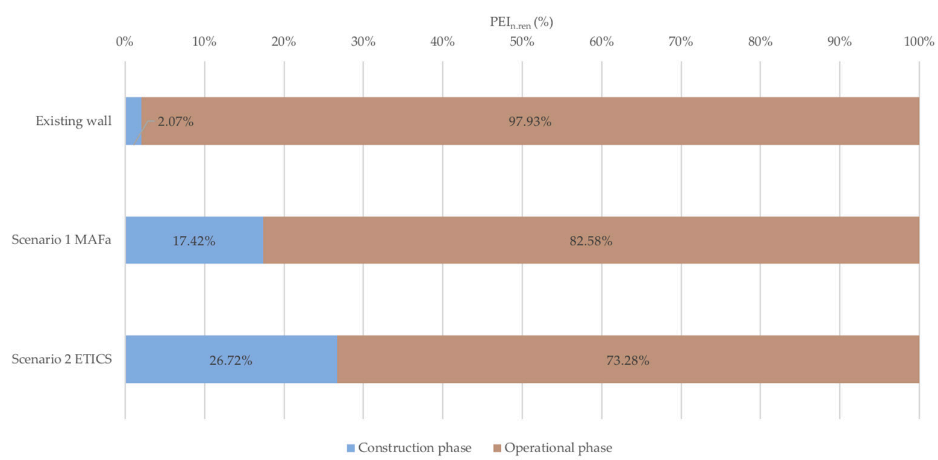


Figure 8. Building 1—comparison between construction- and operational phase regarding $PEI_{n.ren}$.

It can be seen that the material impact of Scenario 1 is with 17.42% of the total impact considerably lower than Scenario 2 with 26.72%. Similarly, the GWP100 is in the MAFa Scenario with 19.97% also much lower than the overall percentage of the construction phase of the ETICS variant with 30.55%. In the existing wall the impact of the operational phase is evidently the highest. As the quality of the original building stock is relatively low, compared to the refurbished scenarios where the thermal envelope has been fully exchanged, the energy required to operate the building by far exceeds the energy input of the basic construction. Thus, an improvement of the building shell is in any case a positive way forward.

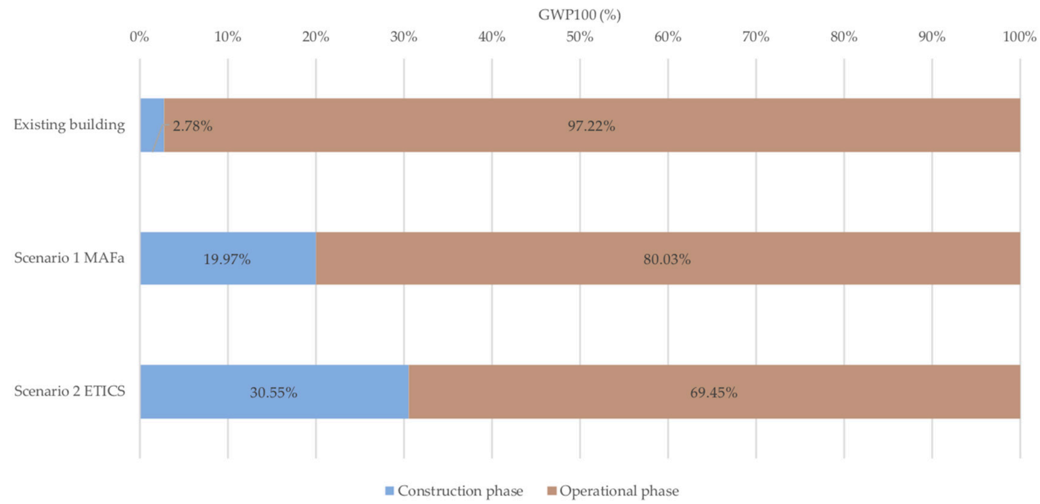


Figure 9. Building 1—comparison between construction- and operational phase regarding GWP100.

6. Discussions

The results highlight the importance of a holistic life cycle approach to support the choice of materials or systems with a low environmental impact. To expand the view of the operational phase towards the overall life cycle marks an important step towards the reduction of the environmental impact in construction.

The lifetime of the construction used for refurbishing the building contributes considerably to the required energy input. In the case study the $PEI_{n.ren}$ of the MAFa is −43% (Table 10) and the GWP100 −46% (Table 11) compared to the ETICS façade. This is also due to the much higher life expectancy of the MAFa with 50 years compared to the ETICS with only 35 years. However, it must of course be noted that any new construction (and thus any refurbishment actions) add to the GWP as new materials are applied. Thus, choosing a façade system with a high life span is one of the prerequisites for reducing the overall environmental impact. Similarly, this logic should also be applied for new buildings. Looking at the construction phase and thus the material impact of the system before operation only, the MAFa system shows 17% of construction impact in relation to the total life cycle compared to the ETICS with 27%.

When comparing a standard ETICS façade system with the novel Multi-Active Façade solely on the basis of the operational phase, the ETICS would achieve similar primary energy demand savings as the novel façade, due to similar thermal conductivity properties. However, once the $PEI_{n.ren.}$ and GWP100 are calculated including the construction phase, the results show a highly different picture as the Multi-Active Façade has a significantly lower environmental impact over the whole life cycle. This is mainly due to the innovative design and inherent environmentally friendly material properties of the façade, which consists of a cellulose insulation board based on recycled paper as insulation material and in addition makes use of passive solar gains. To understand the extent of those savings, if the MAFa is applied to the existing building, 52 apartments could be fully supplied with energy for 100 years with the amount of $PEI_{n.ren.}$ saved within 100 years, that is 4 apartments more than with the ETICS. Thus, the novel façade could save 10.151 t of CO_2 in comparison to the existing building.

The study highlights that whilst the evaluation of the operational phase alone results in a similar ecological footprint of the ETICS, the analysis over the whole life cycle provides a clear positive indication for the novel Multi-Active Façade.

Whilst the case study is focusing on one particular building in Vienna, the potential for the overall building stock of the same social housing provider has also been assessed. Based on the initial results of the case study, estimates for the application of the novel façade system for additional buildings owned by the same company have been calculated. Only buildings with similar framework conditions have been considered for this assessment. This included that the main façade had to be south facing without major shading by other buildings, trees or infrastructure. From a dataset of 195 buildings, which were in line to be refurbished within the following years, 40 objects with a total gross floor area of 202,300 m² were considered suitable for renovation with the Multi-Active-Façade. If the novel facade would be applied to those buildings, an additional 33,356 MWh/yr of PEIn.ren. and 8837 tCO_2/yr could be saved compared to a conventional system. As outlined above, the application of the MAFa should be limited to unshaded south facades, so that the benefits of the system could be fully exploited. The facade is however particularly suitable when noise reduction is a specific requirement.

The study shows that, as buildings become more energy efficient, an analysis of the whole life cycle of building materials and especially of primary energy demand and global warming potential becomes increasingly important. This is of particular relevance in order for planners and developers to make informed decisions about the choice of construction measures. Especially for building refurbishment the impact of the materials must be considered. This is due to the fact that the overall life span of buildings increases again significantly once the building gets a new thermal envelope. Increasing the relevance of LCAs in construction work would thus support the efforts in decarbonizing the European building stock and ensuring that materials with minimal environmental impact are applied.

In further research projects the assessment of other innovative building construction measures should be addressed. Specifically, those based on recycled or natural resources should be evaluated in comprehensive LCA assessments. Whilst this study focuses on a practical approach within a case study, further theoretical analysis, including costs over the whole life-cycle of the building would also be beneficial. Nevertheless, to carry out comprehensive assessments can be a time-consuming exercise. As stated above, other research in this context already outlined that a simplified and easily applied LCA methodology and tool would be beneficial. This would ensure that LCA assessments would be more widely used by planners and developers and would thus become part of decision processes within the design phase.

Author Contributions: S.S. contributed mainly to the Conceptualization, Analysis, Methodology, Writing and Project Management; D.Ö. contributed mainly to the Analysis, Validation and Writing.

Funding: This research was funded within the project Multi-Active Façade (MAFa), under the framework "Building of Tomorrow" by the Austrian Research Promotion Agency (FFG) with the project number 840645.

Acknowledgments: Supported by the University of Natural Resources and Life Sciences, Vienna Open Access Publishing Fund.

Conflicts of Interest: The authors declare no conflict of interest.

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