REPORT
DELIVERABLE 2.4

outPHit WP2
Reliable Deep renovation Systems

Innsbruck, 25/04/2023,

IDENTIFY TECHNICAL EQUIPMENT PACKAGES (TASK 2.3)

Last updated 25/04/2023 by University of Innsbruck

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OUTPHIT – DEEP RETROFITS MADE FASTER, CHEAPER AND MORE RELIABLE

outPHit pairs such approaches with the rigour of Passive House principles to make deep retrofits cost-effective, faster, and more reliable. On the basis of case studies across Europe and in collaboration with a wide variety of stakeholders, outPHit is addressing barriers to the uptake of high-quality deep retrofits while facilitating the development of high-performance renovation systems, tools for decision making and quality assurance safeguards. **outphit.eu http://www.klimabuendnis.org/**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 957175. The presented contents are the author's sole responsibility and do not necessarily reflect the views of the European Union. Neither the EASME nor the European Commission are responsible for any use that may be made of the information contained therein.

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IDENTIFY TECHNICAL EQUIPMENT PACKAGES

INTRODUCTION

Reducing the energy demand of the building stock is one of the biggest challenges facing the EU. Energy policy objectives are therefore to improve the energy efficiency of existing buildings, which are mainly represented by residential buildings (approx. 75%), and to promote the development of renewable energy sources [1]. Energy efficiency measures include improving the thermal envelope of buildings (e.g., by applying insulation layers to exterior walls and roofs and replacing the entirety of existing windows with high-energy windows) and improving the energy efficiency of heating, cooling, and lighting systems. These measures are necessary to approach the net ZEB standard.

AIM OF THE REPORT

The suitability of available technical retrofit packages depends on the building typology, the location of the building and the local environmental conditions. For example, for buildings without existing ventilation systems, decentralized ventilation via individual room ventilation units can often be more recommendable, as the installation of ventilation ducts and/or the installation of a central ventilation system in the existing building is usually technically impossible and/or associated with high investment costs. In addition, depending on the conditions of the existing situation and in the context of the technical refurbishment, an integration of renewable energies and storage concepts may be recommended. This report is therefore intended to provide an overview of the prerequisites for individual refurbishment concepts and, as a result, to make recommendations for the type of technical refurbishment that can be derived depending on the existing situation.

PREFABRICATION AS A KEY-TECHNOLOGY FOR NZEB

IDENTIFICATION OF THE BASIC REQUIREMENTS

With more than 70% of residential buildings older than 30 years, renovation is becoming increasingly important [2]. The use of prefabricated modular multifunctional renovation elements offers the potential to reduce the time required for the renovation measure and thus reduce the level of disruption to residents, while at the same time improving quality and performance in terms of energy efficiency, building physics and indoor climate [3] [4]. The industrial prefabrication of façade elements including the top layer offers the further advantage of avoiding the risk of increased building moisture in connection with reduced on-site installation times. Energy improvements can be achieved both in heating periods and in cooling periods. Although prefabricated renovation systems are associated with high investment costs, they can be refinanced through the reduced heating demand.

In their work on prefabricated timber elements for sustainable building refurbishment, Sandberg et al. highlight the following requirements that enjoy a high priority from the customer's point of view [4]:

- Positive effects on architecture (building physics, appearance, energy efficiency) and living quality
- Long service life of the materials used
- Low investment costs and short payback periods
- High flexibility to accommodate individual building designs
- Short Installation Times

However, the serial renovation must ensure that the building is physically harmless. This includes thermal and moisture protection as well as air tightness. Furthermore, fire, sound and driving rain protection must be ensured [5]:

In addition to minimizing heat loss, thermal insulation also includes ensuring a comfortable and hygienic indoor climate and reducing the formation of condensation on the inner surfaces of building components [6]. Moisture protection includes the protection of buildings against the effects of water [6]. Moisture protection is decisive for the longevity of the façade. To prevent the formation of mould, the temperature on the inside of the façade must not fall below the guideline value of 12.6°C (surface temperature) [7]. Compared to the horizontal component of the rain (strongly wind-dependent), a high requirement is placed on the impermeability of the façade, especially joints [7].

Furthermore, there are requirements for fire protection. In the area of high-rise buildings in particular, legal requirements must be met (e.g., F90 wall). In the context of fire protection, Le Levé et al. state in their work that double planking is necessary for 90min fire protection [8]. The following figure illustrates a concept

implementation of required fire protection measures using the example of a high-rise building:

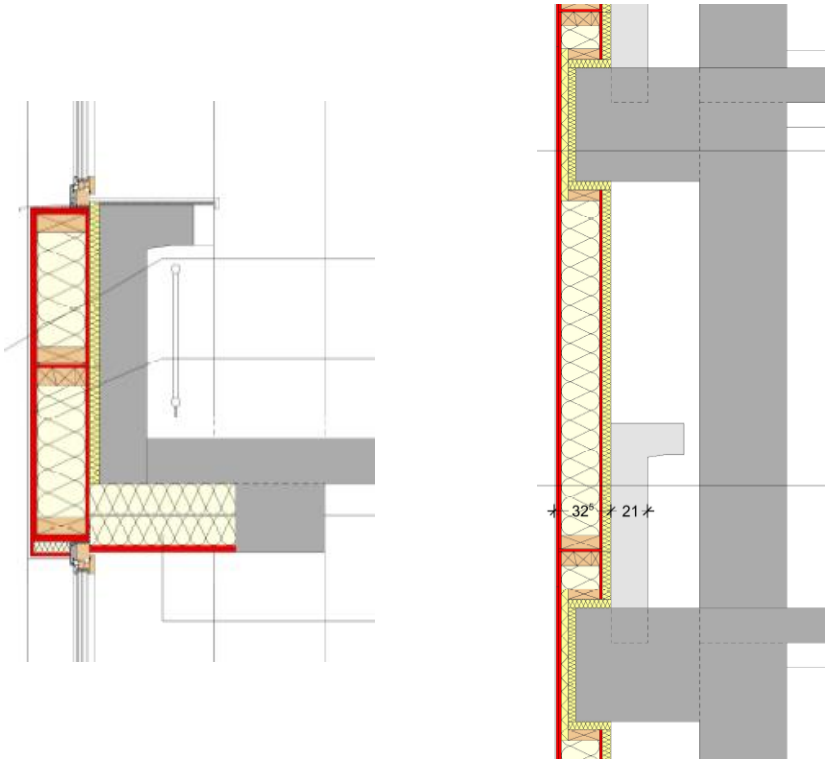

Figure 1: Fire protection measures using the example of a high-rise building for the parapet area (left) and continuous wall surface (right). Image source: [5]

Air tightness is another basic prerequisite for the suitability of the construction in terms of building physics. The purpose of this is to minimize ventilation heat loss and to avoid condensation. The latter refers to the transition of warm room air and cold component layers of the exterior wall. In serial renovation, the airtight layer can be either on the existing interior wall or on the outside of the existing wall. The inclusion of the windows is crucial [5] [6].

If the additive façade elements are not fixed directly to the existing wall, e.g., because the assembly layer requires it and consequently the air tightness is no longer ensured, other concepts must be used. For this purpose, Sandberg et al. present wall elements that are combined in different sizes by assembling the façade elements horizontally and/or vertically with a tongue and groove joint. Bonding of the joints and covering of the insulated spaces with a membrane serve to complement the airtightness of the renovation layer [4]. There are test procedures for testing the airtightness that are standardized in EN 13829.

SYSTEM MODULARITY

In their work, Torres et al. present a plug & play façade construction system based on modular system components. The modules can take on different functions without removing the original envelope: adding insulation, improving the airtightness of the building envelope, replacing windows, and integrating PV or solar thermal and HVAC systems (figure below) [9].

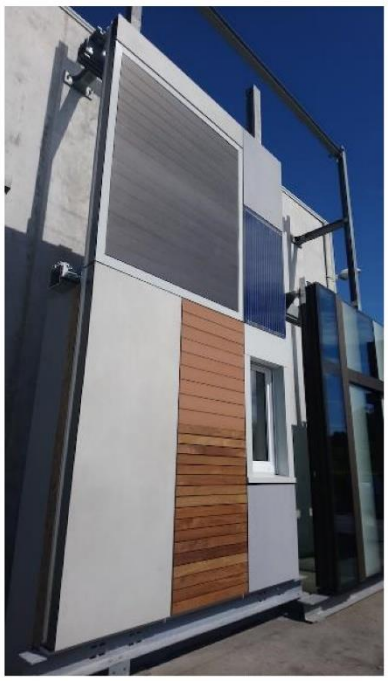

Figure 2: Different finishes and systems of the plug and play façade module. Image source: [9]

The use of active energy-saving measures in the façade (e.g., PV and solar thermal energy) in combination with passive components (thermal insulation) can, in the best case, reduce the use of conventional fuels to zero (NZEB - nearly zero-energy buildings). In terms of energy policy objectives, the integration of active energy-saving measures proves to be necessary. For this reason, systems that offer the integration of green energy generation systems are analyzed in detail in this report.

The modular timber façade system by Sandberg et al. for energy retrofitting of residential buildings offers a high degree of flexibility by adjusting the length of connecting bars and can be adapted to timber, concrete, and brick structures [4]. The adaptability to different types of building structures, materials, tolerances, geometries, and energy requirements makes the modular timber façade system very applicable and efficient. The adaptability to irregularities of the existing structure is identified as a major challenge for the use of modular façade systems [9].

Variable module sizes (1200mm to 3000 mm – fig. 2) and a dynamically scalable assembly level (limited only in module size), as presented by Torres et al., allows on the one hand to compensate for irregularities of the building envelopes and to

serve the architectural characteristics of the individual buildings [9]. The properties of the insulation layer can also be modularly adapted to the requirements of the respective building regulations and climate zones [9].

MOUNTING

In a renovation project, it can be difficult to locate the necessary load-bearing structures, as detailed drawings are often missing, and the walls have not necessarily been realized according to specification. In addition to measurement techniques to determine suitable fixing points, different module sizes can not only absorb unevenness in the building structure, but also bridge weaker wall structures that are unsuitable for mounting the wall brackets [4]. Unevenness can result from demolition of existing cladding to identify suitable fixing points. Maximum module sizes are also determined by transport restrictions and accessibility at the building object (e.g., option for crane use).

In [5], a concept for the application of the Sherpa Efcon façade connector [10] in a high-rise context is presented. The independent assembly of the modules and the associated exchangeability of the modules are highlighted as system advantages of the façade connector. In comparison, a module exchange in the case of element-overlapping force transfer would be associated with a temporary auxiliary load transfer or would result in the dismantling of elements above. Furthermore, the compensation of tolerances in all directions is mentioned as an advantage [5]. The following figure illustrates the application principle of the façade connector:

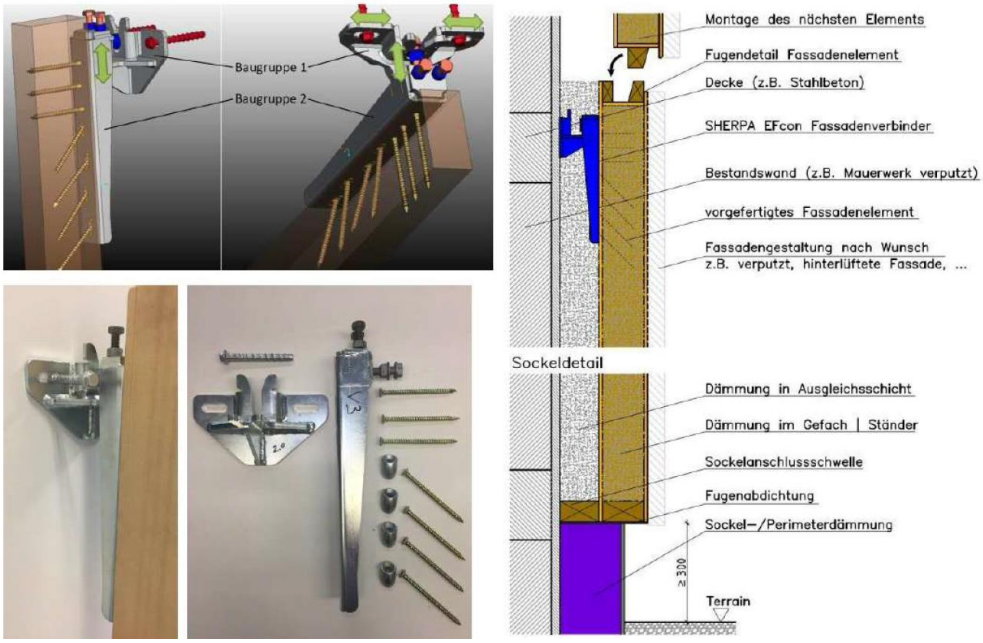

Figure 3: Sherpa Efcon Facade connector. Image source: [5] (original source: [8]).

According to TABULA, these buildings are mostly made of concrete [11]. This offers a great opportunity for building renovation, as façade connectors can be well attached to it. In this context, it proves to be of crucial importance that high-quality

information about the condition of the existing façade is obtained with the help of modern technologies such as topographic surveys or 3D scans and point clouds [9].

CASE STUDIES FROM THE LITERATURE

Sandberg et al. present prefabricated timber façade elements whose height is oriented to the floor height with a length of 4m to 8m, oriented to the concrete partition walls. The thin elements consist of, among other things, 18mm plywood panels, 100mm insulation, 25mm non-combustible windbreak panel, 32mm ventilation gap and customized façade panel. A low thermal bridge area in the module is designed to reduce the risk of condensation. The façade elements are either mounted on mounting battens or directly attached to concrete elements, if available. Fire barriers are provided to prevent the spread of fires [4].

With a thickness of approx. 200 mm of the façade elements in [4], an integration of ducts of the technical finishing trades can be ensured in most cases (follow-up chapter: *HVAC IN PREFABRICATED MODULAR FACADE PANELS*).

For their part, Torres et al. present a modular system that is suspended from brackets that must be installed in the façade beforehand. During installation, the panels are first positioned vertically (including the anchoring) and then finally fixed horizontally (figure below). Inner insulation layer and polyamide profiles are used to avoid thermal bridges in the façade system [9].

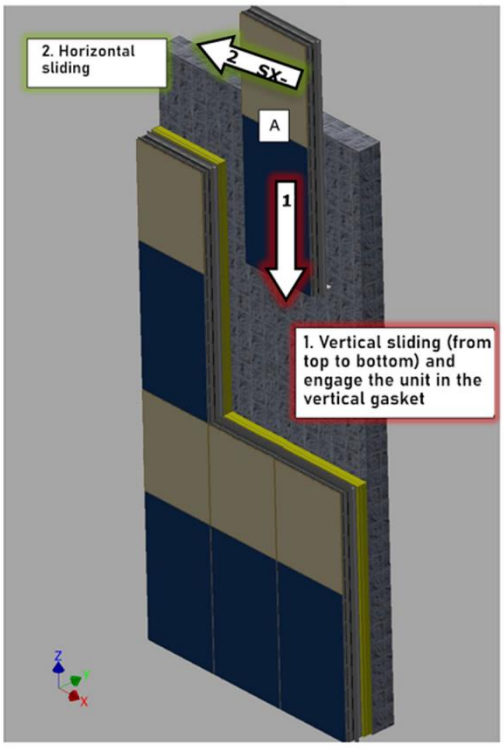

Figure 4: Connection between panels - System's anchorage design, with possibility of adjustment in the "y" axis and in the "x" axis and guarantee load transmission and intermediate element for hanging panels and adjustment and leveling. Image source: [9]

In this modular system concept, the modules of the lower row are fixed to four anchor points. The modules above are only attached to two load-bearing anchor points, as the higher levels are supported by the lower panels. In this context, structural integration with the existing structure is crucial, as the panel deadweight creates additional loads that must be taken up by the existing structure. The load-bearing capacity at each anchor point should be determined in advance for this purpose. The anchors are mounted to the supporting structure [9].

The system's special feature is that the outer surface can be customized (cf. fig. 2). Fibre cement, aqua panels, ceramic tiles, and wood are used as passive energy-saving components of the renovation layer. As a rule, an air gap of 64mm is provided between the insulation layer and the cladding in this concept, on the one hand to enable the dissipation of water vapour and to secure an installation level (e.g., electrical for PV) [9].

WINDOWS

The original windows are removed, and a new sill is installed on the inside of the window. The size of the windows is usually limited by the size of the façade elements. Since larger module sizes can usually be implemented, typical window sizes can be easily integrated into residential buildings that are being renovated. In addition, shading systems such as roller shutters or blinds can be integrated in the renovation layer.

SUMMARY OF THE CONDITIONS OF APPLICATION

- According to [12] (cited in [5]), the construction process for prefabricated façade elements results from: (1) stocktaking (including surveying), (2) module selection (incl. size), (3) concept for module fastening (to the wall and/or in the module composite), (4) securing the module materials with regard to heat, fire, moisture and sound insulation as well as statics.

- It is necessary to create a layout of all components, panel modules and fastening systems already in the design phase. This is because a model obtained from a point cloud, for example, can facilitate the definition of the anchorages [9].

- Anchoring system of modular façade systems must allow high tolerances to adapt to the irregularities of the façade.

- Mounting additive insulation elements on damp walls can create a risk of condensation at the interface. The risk of condensation can be avoided with ventilated façade systems [13]. Some studies have looked more closely at the hygrothermal behavior of renovated solid walls and recommend the installation of a vapour barrier and insulation with a good moisture buffer effect [3] [14].

- Prefabricated renovation can be carried out using self-supporting wall elements as well as non-load-bearing elements. In the case of self-supporting elements, the installation of a wall base is necessary to absorb the vertical loads. A prerequisite for the use of non-load-bearing lightweight walls is that the load-bearing structure in the existing façade can bear the dead load of the additive elements [4].

HVAC IN PREFABRICATED MODULAR FACADE PANELS

VENTILATION INTEGRATION - INSTALLATION AND INSULATION

Energy-efficient façade renovation is accompanied by greater air tightness and thus a reduction in draughts [4]. Due to the higher air tightness, the natural air renewal decreases, which can impair the indoor air quality, whereby the artificial air renewal, or manual air renewal, gains importance to ensure an indoor air quality in terms of the well-being of the occupants. [15].

In their study, Pihelo et al. present modular wall elements with a total thickness of 340mm to 380mm, of which approx. 300mm to 340mm is thermal insulation (u_{wall}=0,11W/m²K) [3]. Within these modules, ventilation ducts are drawn (Ø=approx. 125mm), as a subsequent installation of ventilation ducts within the flats does not appear possible due to a lack of space. By integrating the ducts in the façade element, controlled air renewal can take place and thus improve the indoor air quality. The system is installed in a 5-storey student residence in Estonia [3]. In the study by Pihelo et al., a preheating of the supply air ducts is further presented [3].

Integrating the ventilation ducts within the external façade offers the advantage of saving space, time and costs when renovating residential buildings. The challenge is to distribute the exhaust and supply air ducts across the external façade without losing heat. In the context of outPHits, the energy refurbishment of the building envelope, there are several different methods for installing ventilation ducts in the façade that avoid heat loss. These methods include:

- The installation of the ventilation ducts on the existing wall, and the filling of insulation material around the ventilation ducts. Here, special attention must be paid to good documentation to ensure that ventilation ducts are not damaged by subsequent fastening work of the new insulation level. This type of installation offers the highest degree of flexibility regarding the course. However, this is done under the restriction of increased installation efforts (time and costs).

- The use of insulation material with pre-cut and removable elements for the integration of ventilation ducts as required. Here, different directions of the ventilation ducts can be made possible through various cuts in the insulation material. The advantage of such renovation systems is a high degree of flexibility and minimally invasive installation. Fraunhofer ISE has developed corresponding concepts for this, in which ventilation ducts are integrated into the external insulation. The ventilation ducts are then in turn distributed over the outer façade and below the insulation level (cf. [16] and [17]).

- A factory integration of ventilation ducts in prefabricated façade elements. This concept was tested in the context of prefabricated timber façades in the CCEM research project of the University of Applied Sciences Northwestern Switzerland (FHNW) and using the half shells of the company Flumroc AG. A simple plug-in system is used to connect the ventilation pipes to each other. The prefabricated wall modules are placed on top of each other. The construction site must ensure that the ventilation pipes are brought together manually during installation. A tight connection of the ventilation pipes is guaranteed by double lips. When laying the half-shells, an offset is necessary to meet fire protection and sound insulation requirements. The ventilation offset can be made as a narrow shaft, formed by narrower module elements. The following illustrations are intended to show the procedure (contents from [18]):

Figure 5: Assembly sequence for connecting the ventilation pipes when placing corresponding additive façade elements on top of each other; from left to right: pull out telescope, align ventilation pipe, connect ventilation pipes. Image source: [19] (quoted from [18]).

Figure 6: Representation of two stacked timber façade elements with connected ventilation pipes. Image source: [19] (quoted from [18]).

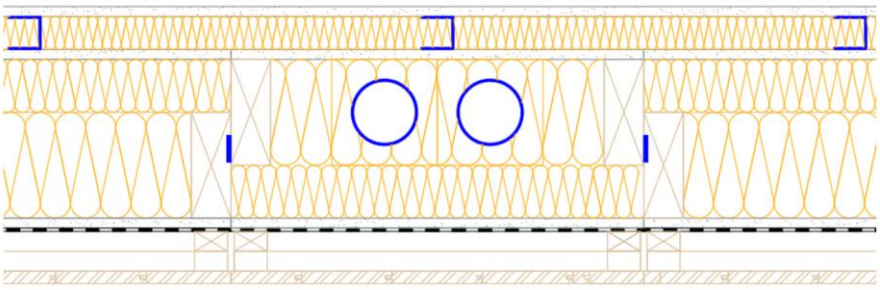

Figure 7: Laying the half-shells in an offset pattern to meet fire protection and soundproofing requirements. Image source: [19].

For ventilation integration, at least 8cm to 12cm over-insulation of the ducts is recommended [17]. When installing the ventilation ducts in the insulation level of the exterior wall, only core drillings need to be made in the target rooms, which keeps disruptive interventions for the occupants to a minimum. Alternatively, it is also possible to use prefabricated multifunctional window modules. For this purpose, Fraunhofer ISE offers a multifunctional window module for integration into the prefabricated refurbishment of the building envelope (cf. [20]).

Possible ways of integrating ventilation ducts in renovations within buildings are the use of free ducts and faced riser shafts for vertical runs (fire protection aspects must be considered here) and suspended ceilings, floor construction and the use of decorative ventilation ducts for horizontal runs. In the case of lagging, particular attention must be paid to hygienic requirements, as cleaning must be ensured (cf. [17]).

HEAT PUMPS - INSTALLATION AND INSULATION

A modular heat recovery unit integrated into the ventilated façade cavity is presented by Martinez et al. [15]. This system concept is suitable for use in multi-floor residential buildings and offers the function of recovering heat from the ventilation air. This allows ventilation air to be preheated in the cooling period and precooled in the hot period. Due to their small depth and low cost, fixed-plate heat exchangers are very well suited for integration into façade elements [15].

Heat recovery is not required, but by using mechanical ventilation with heat recovery, heat losses are reduced, and a high level of thermal comfort can be guaranteed. Supply air heating also makes it possible to dispense with conventional heating systems. This can reduce costs. For passive houses, heating with heat pumps and heat pumps compact units as well as heating with biomass boilers supported by solar systems have turned out to be the preferred heating systems. Heat pumps for passive houses usually require low outputs, typically in the range of 1.5 to 2.5 kW [21]. A first practical demonstration was carried out in the EU project iNSPiRe in a demo building in Ludwigsburg, Germany (exhaust air heat pump, approx. 1 kW in combination with a ventilation unit, in façade integration) [21].

Heat pumps (HP) are a widely used option to achieve energy efficiency improvements in the building sector [22]. The micro heat pump with MVHR (Mechanical Ventilation with Heat Recovery) is even a possibility to integrate HVAC in a prefabricated façade due to its small footprint. An insulation layer of approx. 300mm is required for system integration [23], which would be given with the façade modules presented in [3]. Heat losses through the façade-integrated components are in the acceptable range [23].

However, lower thicknesses of the façade elements with heat pump integration could also be realized. The necessity of the required insulation thickness results from the avoidance of condensation effects between the heat pump and the existing wall, which can occur with insufficient insulation. Therefore, a thin strip of

good insulation (e.g., aerogel thermal insulation) is required between the heat pump and the existing wall. Module thicknesses of approx. 25cm could find greater application in practice in the next few years.

Since the installation involves only one breakthrough and minimal installation within the flat, disruption times for the residents remain reduced. The system use of micro-HP and MVHR is designed for very energy-efficient buildings that have heating loads in the range of 10 W/m². The source of the micro-HP is the extract air. Additional system requirements are pre-heating, auxiliary heating for peak load coverage, maintenance accessibility from outside and optional supplementary bathroom radiators [23]. Although exhaust air heat pumps often require a supplementary system, they can cover a relevant part of the heating/cooling energy demand for air conditioning and allow a remarkable reduction of primary energy demand due to their high average seasonal yield.

In the SaLüH! research project (see [21]), concepts were developed for the façade integration of a drinking water heat pump including a storage unit and a heating-ventilation heat pump. In the process, integration possibilities in a lightweight timber curtain wall and in the parapet area below a window were considered. The domestic hot water heat pump and storage unit were only evaluated theoretically. A functional model was developed for the heating-ventilation heat pump. The integration of heat pumps in curtain walls enables a high degree of prefabrication and minimizes installation efforts. The challenge lies primarily in the availability of space within the façade at reasonable costs.

Figure 8: Functional sample of a prefabricated wooden façade with integrated outdoor unit of the heating-ventilation-heat pump. Image source: [21].

The prefabricated façade from the functional sample consists of the following components:

- A wooden frame.
- A wooden panel covering the mineral wool thermal insulation inside and outside.
- A cement-bonded chipboard cladding.

Another possibility is the integration in the curtain wall (concept illustration in the following figure). The advantage here is the larger space available, which ensures integration of the heat pump [21]. Behind the outdoor unit, a more powerful insulation board is used so that critical temperature conditions do not occur despite the lower insulation thickness. In addition, a vapour-barrier membrane is installed on the inside and an airtight membrane on the outside. The test façade is 31cm thick [21].

Figure 9: Possibility of integrating storage tank and heat pump in a curtain wall. Image source: Vaillant, sourced from [21].

Solutions for heating and hot water production in multi-storey residential buildings based on decentralized micro heat pumps in combination with a ventilation unit are promising but require further research and development.

SUMMARY OF THE CONDITIONS OF APPLICATION

- Façade-integrated heat pumps usually require additional systems for heat generation and cooling. As a further technical requirement, these need maintenance accessibility and thicknesses of the façade modules of at least 300mm. [23].

- Ventilation ducts are installed in the cavity. The air intake in the rooms is usually provided on the sides of the windows. Ventilation fans and heat recovery systems are mounted in easily accessible places for maintenance (figure below). Usually near stairwells or plant rooms.

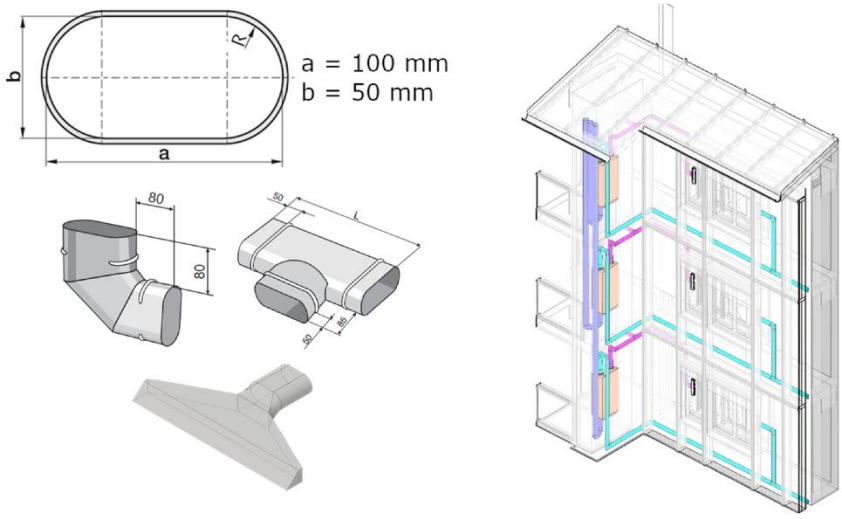

Figure 10: Ventilation system: components (left) and system concept (right). Image source: [9]

- Multifunctional façade elements enable the flexible installation of HVAC systems (e.g., ventilation ducts), electrical supply lines and ICT lines within the insulation elements to minimize disruptions for users. Existing building services systems and utilities can thus be successively replaced. Over-insulation of 8cm to 12cm is recommended for pipe runs [17], in order to avoid thermal bridges and to prevent strong cooling (winter) or heating (summer) of the fresh air [18].

CONVERSION OF SOLAR ENERGY

PV AND SOLAR THERMAL FOR ENERPHIT-PLUS AND -PREMIUM

While the refurbishment of old buildings with passive house components helps to reduce the energy demand and achieve the EnerPHit standard, the supplementary integration of renewable energies can further reduce the costs for energy procurement. Depending on the use of renewable energy in connection with the renovation of an old building, the EnerPHit classes Classic, Plus or Premium can be achieved [24].

Great progress has already been made in solar technology. This concerns photovoltaics, solar thermal as well as the combination of both. Therefore, these are considered the most feasible solution for integrating renewable energies in building applications [25]. In terms of local energy generation, photovoltaics (PV) offers great potential for providing sustainable electrical energy [26]. This is especially true in an urban context [26]. However, compared to photovoltaics, solar thermal energy has a 2 to 4 times higher efficiency in the conversion of solar energy [27]. Solar thermal and PV are a good way to reduce energy costs and achieve a high EnerPHit standard in the context of refurbishing old buildings.

This means that buildings are faced with the task of achieving an energy requirement minimum and an electricity generation optimum in addition to functionality and aesthetics. Buildings will therefore become small power plants in the future. The following functional requirements must also be placed on combined additive façade elements consisting of active energy-saving components and an insulating layer:

- Weather protection
- Insulation
- Sound insulation
- Aesthetics (coloring conceivable)
- Air conditioning
- Thermal insulation

CATEGORISATION

According to [28], three categories can be identified about the structural integration of photovoltaics. The type of installation influences design, costs, and efficiency. These basic categories can also be applied to solar thermal energy:

- *Integration level I: Application (visual integration) - additive integration*
  Integration level I comprises those applications where the PV or solar thermal modules are additionally installed in front of or above the actual building envelope. This is of high practical relevance for renovation. Apart from a few structurally necessary points, the system does not enter any

further structural connection with the building, which means that no significant changes to the existing structure and the functions of the building envelope are required.

- *Integration level II: Constructive addition - substitution*
  In this category, the PV or solar thermal modules are seen as part of the building envelope and are structurally connected to the structure. By serving as weather protection, they take over the main function of the outermost layer. This is of high practical relevance in the context of serial refurbishment, as in this function an increase in efficiency can be achieved through rear ventilation in the case of PV, the risk of overheating in the case of solar thermal systems is avoided and challenges of air tightness are not on this level.

- *Integration level III: Constructive integration - full integration*
  PV or solar thermal modules are components of the warm façade or the roof covering. As components of the building envelope, they take over all its functions, such as weather, thermal, solar, and sound insulation. Warm roof constructions are usually associated with air tightness challenges due to the installation of fastening anchors.

Possibilities for building integration, from left to right: on the sloping roof, in the sloping roof, on the flat roof, in the flat roof, in front of the façade, cold/warm façade, skylights, sun protection. Integration of PV in glass facades, skylights, parapets, and solar shading technology is possible, but will not be the focus of this report. It has been shown that the investment costs of building-integrated solutions are 20% to 30% higher than for rooftop systems [28].

BUILDING INTEGRATED PHOTOVOLTAIK - BIPV

In their study, Evola and Margani investigate the energy and economic viability of retrofitting residential buildings in a moderate climate using Building Integrated Photovoltaics (BIPV) [1]. It is shown that the NZEB standard target for single-family houses can largely be ensured by using the building roof area as PV area. For multi-family houses (and especially > 5 floors), this is usually not the case. BIPV is a good solution for these buildings.

The major challenge compared to roof mounting is the mutual shading of buildings, especially in an urban context [29] [30]. However, BIPV offers the advantage of distributing energy production throughout the day by placing modules on different façade orientations. BIPV concepts can also help to improve the thermal transmittance of the building envelope and thus reduce the heating energy demand [31] and ensure compliance with EN 50583 and IEC-TS 61836 [29]. Especially the last point should be emphasized in the project context of outPHit, because BIPV should be considered as a multifunctional element that contributes to energy production and building envelope improvement. Regarding the normative situation, DIN VDE 0126-21 "Photovoltaics in the building sector" (original: Photovoltaik im Bauwesen) must be mentioned for German-speaking countries,

which describes detailed requirements for safety, product verification and construction product guidelines, quality and reliability, planning, installation and building integration.

Saretta et al. therefore dedicates their studies to the investigation of the BIPV retrofit potential of facades. Their approach focuses on an evaluation at the urban level [29]. districtPH is used to derive renovation and development scenarios for the building stock at the neighborhood or city level. Energy balances are created. Electricity and heat networks, renewable energies, electromobility and public consumers are included in this balance [32]. A parallel consideration or expansion to include BIPV retrofit potentials according to [29] can be recommended.

The profitability of BIPV is significantly linked to the climatic location and the orientation of the building, in addition to the building's own demand and the building's statics. In their work, Evola and Margani show that there are strong fluctuations in the absolute values of electrical energy demand for lighting, appliances, heating, and cooling in relation to the geographical location [1]. The energy demand for lighting and electrical end-uses is relatively constant. The differences result predominantly from electrical heating sources and cooling appliances. In the north of Italy (Milan), the additional electrical energy demand for heating and cooling is twice as large as in the south of Italy (Catania) - Comparison based on measurements in kWh/m²a. In the north, approx. 80-90% of the additional electrical energy demand is for heat generation. In Catania it is approx. 30%. In Rome, there are relatively balanced shares. Since the absolute value is larger in more northern regions, it can be stated that heat generation is more energy intensive. Furthermore, the heating energy demand measured in kWh/m²a is lower in multi-storey buildings compared to buildings with few storeys.

In addition, it is shown that the potential of BIPV on a south façade is 30% lower than for PV systems with optimal inclination. For east and west facades, this is 50% lower compared to the optimal tilt (applies to northern and southern Europe [33] [34]). Buildings with a north-south main axis (usable area) require almost 20% more PV area compared to the same building with an east-west orientation [1]. This results from the annual electrical energy consumption and the orientation-dependent potentials. Furthermore, the investigations of the BIPV profitability in relation to the location show that in Northern Europe it is more advisable to invest primarily in thermal refurbishment than in BIPV coupled façades [35]. Regarding the amortization of BIPV, the following dependencies can be identified [1]:

- The higher the number of floors in a building and thus the usable wall area for PV, the shorter the payback period.

- The higher the feed-in tariff, the lower the payback period, of course.

PV glass has similar mechanical and strength properties to architectural glass. As PV glass is already a composite material, the requirements of the building regulations are met [9].

SPECIAL CASES WITH BIPV

Solar thermal PVT Austria offers customized solar modules with colored solar cells [36], which can meet the aesthetic demands of BIPV. With the Schüco Energy now concept, AluKönigStahl offers a building-specific combination of high thermal insulation, shading and building services components. Energy is generated by integrating solar thermal and photovoltaic systems [28].

Shading of PV modules can lead to significant yield losses. If shading cannot be avoided, passive modules (even in PV optics) could be placed, or a series connection of many modules should be avoided. A parallel connection would be preferable in this case, as it is associated with lower power and yield losses in the shaded case. In the unshaded case, the series connection is the more cost-efficient solution [28].

If buildings are listed, BIPV and thus the use of additive façade elements is often only possible to a limited extent. Here, local building regulations must be checked. In addition, fire protection regulations can become valid with BIPV; here, too, reference must be made to national/regional building regulations. For Germany, these would include DIN4102 "Fire protection in building construction" (original: Brandschutz im Hochbau) and DIN EN 13502 "Classification of construction products and types of construction for their reaction to fire" (original: Klassifizierung von Bauprodukten und Bauarten zu ihrem Brandverhalten).

SOLAR THERMAL SYSTEMS AND THEIR INTEGRATION INTO FAÇADE ELEMENTS

Solar thermal energy can be installed analogous to photovoltaics in the classic roof structure or integrated into façade components (STF: solar thermal façade, ASTF: active solar thermal façade, summarized below as STF). By integrating solar thermal energy into the building envelope (wall, window, shading, or roof), the STF offers both the function of insulation and thermal energy generation [25]. The increasing industrialization of production in the building industry, e.g., of prefabricated ceilings, prefabricated concrete parts and façade modules, offers the opportunity to integrate the function of STF cost-effectively into these modules. The same applies to heating, ventilation, and shading functions. The distribution structure integrated into the façade. The following figure illustrates the concept of STF as façade modules:

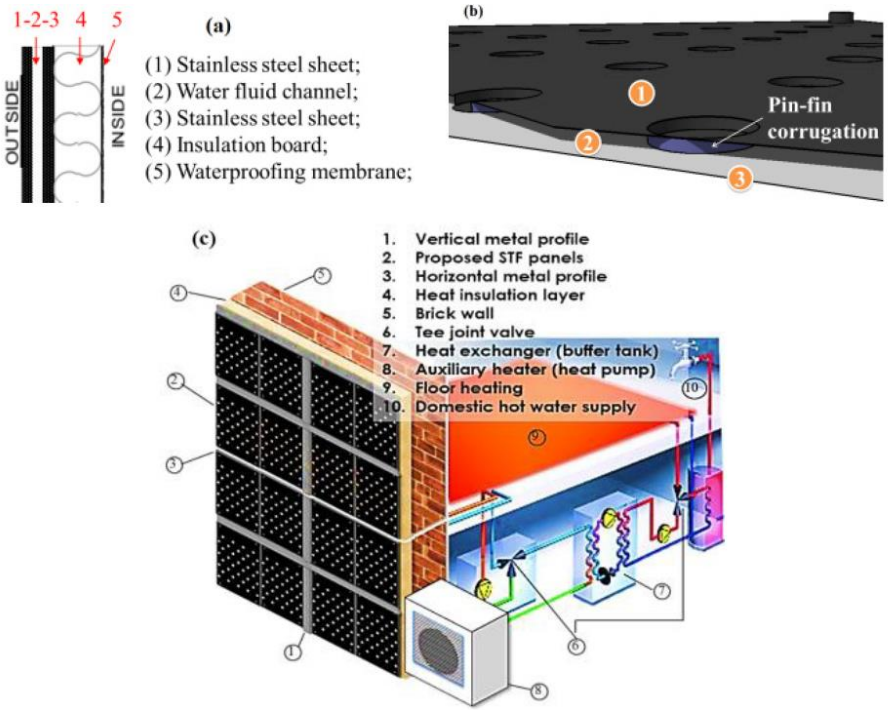

Figure 11: (a) Schematic design of the proposed STF; (b) flow channel of the STF; (c) conceptual wall renovation with the STF. Image source: [37]

The solar thermal system is usually an (un)glazed solar thermal collector integrated into a sandwich panel as an active façade, with the absorber acting as an external cladding [38]. The panel serves as both cladding and absorber. Capillary tubes made of copper are welded to sheet metal tubes. A water-glycol mixture is usually used as the heat transfer medium, which circulates through the capillary tubes. The capillary tubes are located on the outer sheet metal and act as absorbers. The thermal energy thus generated in the medium is transferred to the heat exchanger (usually positioned in the technical room of the building) [9].

In [37], the configuration of a solar thermal façade module with internal extruded flow channel is optimized for different applications. The thermal performance of the solar thermal façade module (STF) is a factor that depends on several design parameters:

- Material
- Color and lacquer type
- Tube diameter and number
- Tube length and vertical distance between tube rows

The results identify stainless steel as the material of the STF and due to the high absorption and low emissivity, selective black for the colored coating. Black chrome has the best performance with the highest thermal efficiency (almost 70 %) and the lowest heat loss coefficient (about 13.17 W/m²). The optimal range for fin diameter was found to be 25 to 40 mm, the number of fin rows 4 to 10 with a fin length of 2.4 to 2.7 mm and a vertical spacing between the fin rows of 60 to 100 [37]. In [39],

the efficiencies of different colored absorbers are analyzed via TRNSYS, with the result of deviations of 7% to 18% depending on the location and selection.

Based on the work of Zhang et al., the advantages and disadvantages of different systems are highlighted below [25]:

- Wall-based systems such as WAF solar facade by WAF-Fassadensysteme GmbH [40]) and MegaSlate (3S Swiss Solar Solutions AG [41]) offer the possibility of improving thermal insulation and integrating pipework within the facade elements. The systems usually consist of a metal plate with a selective treatment as a solar absorber, a liquid cooling circuit connected to the absorber, an insulating layer on the back and protective glazing. Wall-based systems have a high degree of prefabrication and can be compared to the cost of a conventional façade. In addition, the active and economic integration of solar collectors into the top layer means that large collector areas can be implemented. Disadvantages of wall-based systems are additional costs for cleaning and maintenance, risk of overheating and weather resistance of the materials. Condensation and thermal frost within the insulation also pose a risk. The additional loads impose correspondingly high structural requirements. The MegaSlate system uses double glazing and argon gas in the interstitial space to reduce heat loss. The WAF system consists of Cu pipes in an insulated material and conduit sheet optionally protected by weather protection plates. The elements can be connected in series.

- Window-based systems offer the possibility of a high degree of prefabrication, like wall-based systems. Transparent and translucent STF models offer the function of solar heat absorption and daylight transmission. Air-based STF systems have the advantage of low cost but are also less efficient in absorbing solar energy compared to fluid-based STF systems, due to the low density of air. The glazing creates a corresponding weather resistance. A disadvantage is that light transmission is slightly reduced. Furthermore, the requirement for additional movable shading in the open-view area is a necessary system requirement. Due to the temperature load and the associated thermomechanical deformation of the components and the overall system, the reliability of the collector represents the greatest risk of these systems.

- Solar thermal modules can also be integrated as balcony elements. An example is Swisspipe [42], a vacuum tube collector. Since the tube heat absorbers are standardized products that can be easily interconnected and extended, flexible dimensions can be implemented. Advantages include a high degree of prefabrication and good suitability for retrofitting in existing buildings. Due to the complete exposure of the system to the outside situation, there is a risk of weather damage, but easy accessibility for maintenance and cleaning is also ensured.

- Roof-based STFs have a comparable structure to wall-based systems and can be created in a modular structure and thus also represent an economic and highly efficient solution. The similar structure also results in the same advantages (including simplified cable routing, improved thermal insulation of the roof) and disadvantages (including high static requirements). System providers include Tesla [43] and Energie Solaire [44].

The requirements for STF regarding efficiency, safety and durability are laid down in standards. These include, in particular, EN12975 (Solar thermal systems and their components - Solar collectors - Part 1: General requirements + Part 2: Test methods), EN12976 (Solar thermal systems and their components - Factory-made systems - Part 1: General requirements + Part 2: Testing) and EN12977 (Solar thermal systems and their components - Customized systems - Part 2: Test methods for solar water heaters and combi systems + Part 3: Performance test methods for solar water heaters + Part 4: Performance test methods for solar combi cylinders + Part 5: Performance test methods for control devices).

In summary, it can be stated that façade modules with integrated solar thermal energy offer high potential, but their market penetration is currently still limited by the module size and complex structure, the risk of overheating and high investment costs [25]. The increase in industrially prefabricated façade elements offers the opportunity to solve existing obstacles and to put market penetration into perspective.

SUMMARY OF THE CONDITIONS OF APPLICATION

- The use of BIPV is recommended when the usable wall surfaces run in an east-west direction and in apartment buildings with more than five floors. [1].

- STF offer improved operating performance, high collector capacity, the possibility of modular installation, pipe routing within the façade and thus reduced equipment space under the requirement of increased load-bearing capacity, compared to the separate design [25].

- According to [28], the following requirements for BIPV can be identified:

  - Modular system structure given
  - Dismantling possible
  - Rear ventilation available
  - No absorption of mechanical forces (transmission)
  - Materials for anchoring: bricks, fibre cement, natural stones, metals, glass, or plastics, if these are back ventilated and anchored by means of a metal substructure and retaining clips (statement without additional insulation).

ROOF RENOVATION AND ROOF GREENING

ROOF REFURBISHMENT

One method to reduce the high energy demand and the associated CO_2 emissions in the building sector is to increase thermal insulation and thus reduce the heat transfer coefficient. First and foremost, an energetic refurbishment of the entire building envelope is selected as a measure. Studies show that, in certain cases, renovating only the roof of a building is better than renovating the entire building envelope [45]. Borràs et al. show in their studies that especially in warm climates with dry summers, high temperatures and solar radiation, the influence of the roof on the heating energy demand is greater than 50%. Therefore, in these climates, the option of renovating only the roof is an effective solution [45]. The colder the climate, the higher the energy savings resulting from the renovation of the entire building envelope compared to the renovation of the building roof [45].

ROOF GREENING

In the context of thermal renovation of the building roof (flat roof) in an urban context, green roofs represent a method to demonstrably reduce energy demand and CO_2 emissions and consequently improve air quality [46]. In addition, a reclamation of green spaces in the city can be created in this way.

In regions where the need for cooling energy predominates, higher vegetation densities on the green roof show higher energy savings. This is illustrated in [45], which compares three different roof renovation concepts. Variant B and variant C differ only in the thickness of the green roof area.

- Variant A: EPDM Waterproof sheet 0.0012m, 025W/mK, XPS Thermal insulator 4.5-15.5m, 0.033W/mK, Gravel 0.06m, 2W/mK

- Variant B: EPDM Waterproof sheet 0.0012m, 0.25W/mK, Anti-root sheet 0.001m, 0.33W/mK, XPS Thermal insulator 3.5-14, 0.033W/mK, Plastic nodular drainage layer 0.04m, 0.33W/mK, Filter sheet 0.001m, 0.038W/mK, Substrates 0.1m, 0.435W/mK, Vegetation sedum 0.1m

- Variant C: EPDM Waterproof sheet 0.0012m, 0.25W/mK, Anti-root sheet 0.001m, 0.33W/mK, XPS Thermal insulator 3.5-14, 0.033W/mK, Plastic nodular drainage layer 0.04m, 0.33W/mK, Filter sheet 0.001m, 0.038W/mK, Substrates 0.6m, 0.435W/mK, Vegetation sedum 0.4m

On the other hand, in the warmer climates, similar savings are shown between Variant A and C, while Variant B shows the lowest savings [45].

Green spaces with high vegetation densities show good results for the described initial situation in [45]. However, these can be associated with a high dead weight.

For this reason, special attention must be paid to the building statics when using this solution.

ENERGY ROOF

The energy roof is a concept for generating thermal energy via the roof surface without additional collectors and the option of adding PV modules to generate electrical energy. In the renovation of old buildings, especially single-family houses, this system can replace outdated heating solutions and, in combination with heat pumps and ice storage, cover the thermal energy demand of the building in a CO_2-neutral way [47]. Renovation while the building is occupied is possible.

The roof system requires a high degree of absorption and good thermal conductivity to transfer the solar radiation to the heat transfer fluid. The material used is usually coated aluminum in a dark color (cf. *SOLAR THERMAL SYSTEMS AND THEIR INTEGRATION INTO FAÇADE ELEMENTS).* A system concept can consist of energy roof, heat pump, ice storage, switching valve, belly water storage, control, heating circuit and hot water preparation [47]. Underneath the roof system, the insulation and insulating layers are.

Additional ice storage tanks can be installed outside in the ground. Piping from the outside into the technical room is possible. Analogous to solar thermal façade modules, this represents an opportunity to use solar thermal advantages during renovation work.

SUMMARY OF THE CONDITIONS OF APPLICATION

- According to [45], renovating the roof independently of the building envelope is a solution for warm climates with dry summers and high temperatures.

- In addition to high static requirements, green roofs are subject to the prerequisite of regions where the need for cooling energy outweighs that of heating energy [45].

CONCLUSION

The use of prefabricated façade elements offers numerous advantages, such as the standardization and industrialization of the manufacturing processes. This increases the speed of construction and leads to a reduction in execution time and construction costs. In addition, high quality standards can be set through the controlled environment of industrial production. According to various studies, time savings of 30% to 50% and ultimately cost savings of 20% to 40% can be achieved by using modular strategies in construction [48]. Reduced renovation time also reduces disruption to occupants [49], which can be crucial for marketing renovation approaches.

An integration of ducts and system components of the HVAC trades as well as an integration of renewable energies is possible in prefabricated façade elements. Minimum thicknesses for the façade elements of 200mm to 300mm are identified for HVAC integration in the building envelope [4] [23].

In serial refurbishment, it can be difficult to identify load-bearing structures and consider complex building structures. Scalable modular façade elements as load-bearing and non-load-bearing elements offer the required flexibility. The combination of passive components for energy saving (thermal insulation) and active components (PV) can help to reduce the use of conventional fuels to zero (NZEB). In this context, a high degree of system modularity allows the combination of different designs of the refurbishment layer, e.g., a mix of active and passive system components: Insulation layer without active components PV modules with insulation behind them and insulation layer with solar thermal [9].

REFERENCES

[1] G. Evola and G. Margani, "Renovation of apartment blocks with BIPV: Energy and economic evaluation in temperate climate," *Energy and Buildings,* vol. 130, p. 794–810, 2016.

[2] C. A. Balaras, K. Droutsa, E. Dascalaki and S. Kontoyiannidis, "Deterioration of European apartment buildings," *Energy and Buildings,* vol. 37, no. 5, pp. 515-527, 2005.

[3] P. Pihelo, T. Kalamees and K. Kuusk, "nZEB Renovation with Prefabricated Modular Panels," *Energy Procedia,* vol. 132, pp. 1006-1011, 2017.

[4] K. Sandberg, T. Orskaug and A. Andersson, "Prefabricated Wood Elements for Sustainable Renovation of Residential Building Façades," *Energy Procedia,* vol. 96, pp. 756-767, 2016.

[5] M. Dragaschnig, "Machbarkeitsstudie für die energetische Gebäudesanierung mit vorgefertigten Fassadenelementen in Holzrahmenbauweise (Master Thesis)," University of Innsbruck, Innsbruck, 2021.

[6] M. Post and P. Schmidt, Lohmeyer Praktische Bauphysik: Eine Einführung mit Berechnungsbeispielen, Wiesbaden: Springer Fachmedien Wiesbaden, 2019.

[7] W. Heusler and K. Kadija, "Gebäudehüllen gestern, heute und morgen," *Bauphysik Kalender 2017: Gebäudehülle und Fassaden,* vol. 17, pp. 3-44, 2017.

[8] C. Le Levé, T. Badergruber, M. Flach and A. Kraler, "Endbericht - Vorgefertigte Fassadensysteme in Holzbauweise bei Gebäuden mit einem Fluchtniveau von mehr als 22m (Hochhausbereich)," University of Innsbruck, Innsbruck, 2018.

[9] J. Torres, R. Garay-Martinez, X. Oregi, J. Torrens-Galdiz, A. Uriarte-Arrien, A. Pracucci, O. Casadei, S. Magnani, N. Arroyo and A. Cea, "Plug and Play Modular Façade Construction System for Renovation for Residential Buildings," *Buildings,* vol. 11, no. 9, p. 419, 2021.

[10] SHERPA, "SHERPA EFCON Fassadenverbinder," [Online]. Available: https://www.sherpa-connector.com/?LNG=de. [Accessed 01 02 2023].

[11] T. Loga, B. Stein and N. Diefenbach, "TABULA building typologies in 20 European countries—Making energy-related features of residential building stocks comparable," *Energy and Buildings,* vol. 132, pp. 4-12, 2016.

[12] E. Haselsteiner, "plusFASSADEN: Vorgefertigte intelligente Fassadensysteme zur energieeffizienten Sanierung von großvolumigen Wohnbauten," in *öko san'11 - Internationale Konferenz für hochwertige Sanierung und Nachverdichtung mit Holzbausystemen*, 2011.

[13] T. Colinart, M. Bendouma and P. Gluannec, "Building renovation with prefabricated ventilated façade element: A case study," *Energy and Buildings,* vol. 186, pp. 221-229, 2019.

[14] C. Coupillie, M. Steeman, N. Van Den Bossche and K. Maroy, "Evaluating the hygrothermal performance of prefabricated timber frame façade elements used in building renovation," *Energy Procedia,* vol. 132, pp. 933-938, 2017.

[15] A. Martinez, I. Urra, J. Hernandez, T. Diallo and X. Zhao, "Development of a Smart Modular Heat Recovery Unit Adaptable into a Ventilated Façade," *Procedia Environmental Sciences,* vol. 38, pp. 94-101, 2017.

[16] Fraunhofer ISE, "Fassadenintegrierte Heizung, Lüftung, Klima (HLK)," [Online]. Available: https://www.ise.fraunhofer.de/de/geschaeftsfelder/energieeffiziente-gebaeude/gebaeudehuelle/fassadenintegrierte-heizung-lueftung-klima-hlk.html. [Accessed 01 04 2023].

[17] komfortlüftung.at und Energie Tirol, "Spezielle Leitungsführungen in der Sanierung," komfortlüftung.at und Energie Tirol, [Online]. Available: https://www.komfortlüftung.at/einfamilienhaus/sanierungsloesungen/luftleitungen/. [Accessed 2023 04 01].

[18] T. D. Hellthaler, "Entwicklung von Hybridbau-Fertigteilwänden in Holzrahmenbauweise für Gebäude der Gebäudeklasse 5 und den Hochhausbereich," University of Innsbruck, Innsbruck, 2019.

[19] R. Kobler, A. Binz and G. Steinke, "Nachhaltige Wohnbauerneuerung. Vorfabrizierte Fassaden- und Dachmodule. Schlussbericht der Module A3, A4 im CCEM Forschungsprojekt.," Fachhochschule Nordwestschweiz FHNW, 2010.

[20] Fraunhofer ISE, "RetroKit – Vorgefertigte Fassadenkomponenten für die Gebäudesanierung," [Online]. Available: https://www.ise.fraunhofer.de/de/forschungsprojekte/retrokit-toolboxes.html . [Accessed 01 04 2023].

[21] F. Ochs, D. Siegele, D. Jähnig, C. Rohringer, T. Calabrese, R. Pfluger and C. Fink, "Sanierung von Mehrfamilienhäusern mit kleinen Wohnungen – Kostengünstige technische Lösungsansätze für Lüftung, Heizung und Warmwasser - Endbericht zum Projekt SaLüH!," nachhaltigwirtschaften.at, 2020.

[22] F. Ochs, M. Magni and G. Dermentzis, "Integration of heat pumps in buildings and district heating systems—Evaluation on a building and energy system level," *Energies,* vol. 15, no. 11, p. 3889, 2022.

[23] F. Ochs, D. Siegele, G. Dermentzis and W. Feist, "Prefabricated Timber Frame Façade with Integrated Active Components for Minimal Invasive Renovations," *Energy Procedia,* vol. 78, pp. 61-66, 2015.

[24] Passivhaus Institut, "PHI-Webauftritt - Energiestandards," [Online]. Available: https://passiv.de/de/03_zertifizierung/02_zertifizierung_gebaeude/04_enerphit/04_enerphit.htm. [Accessed 01 02 2023].

[25] X. Zhang, J. Shen, Y. Lu, W. He, P. Xu, X. Zhao, Z. Qiu, Z. Zhu, J. Zhou and X. Dong, "Active Solar Thermal Facades (ASTFs): From concept, application to research questions," *Renewable and Sustainable Energy Reviews,* vol. 50, pp. 32-63, 2015.

[26] D. M. Kammen and D. A. Sunter, "City-integrated renewable energy for urban sustainability," *Science,* vol. 352, no. 6288, p. 922–928, 2016.

[27] P. Pinel, C. A. Cruickshank, I. Beausoleil-Morrison and A. Wills, "A review of available methods for seasonal storage of solar thermal energy in residential applications," *Renewable and Sustainable Energy Reviews,* vol. 15, no. 7, pp. 3341-3359, 2011.

[28] H. Fechner, E. Sehnal, R. Haas and A. López-Polo, "Gebäudeintegrierte Photovoltaik Teil 1 - Technologiestatus, Erfahrungen, Best Practice-Beispiele und Visionen der GIPV Technologie; Eine Studie im Auftrag des österreichischen Klima- und Energiefonds," klima + energiefonds, Wien, 2009.

[29] E. Saretta, P. Caputo and F. Frontini, "A review study about energy renovation of building facades with BIPV in urban environment," *Sustainable Cities and Society,* vol. 44, pp. 343-355, 2019.

[30] A. Vulkan, I. Kloog, M. Dorman and E. Erell, "Modeling the potential for PV installation in residential buildings in dense urban areas," *Energy and Buildings,* vol. 169, p. 97–109, 2018.

[31] M. Chiu, S. Hou, C. Tzeng and C. Lai, "Experimental investigations on the thermal performance of the ventilated BIPV wall," *Journal of Applied Sciences,* vol. 15, no. 3, p. 613–618, 2015.

[32] Passivhaus Institut, "districPH - Energieeinsparpotenziale auf Quartiersebene bewerten!," [Online]. Available: https://passiv.de/de/04_phpp/07_districtph/07_districtph.html. [Accessed 01 02 2022].

[33] S. Paiho, I. Pinto Seppa and C. Jimenez, "An energetic analysis of a multifunctional façade system for energy efficient retrofitting of residential buildings in cold climates of Finland and Russia," *Sustainable Cities and Society,* vol. 15, pp. 75-85, 2015.

[34] E. Sánchez and J. Izard, "Performance of photovoltaics in non-optimal orientations: An experimental study," *Energy and Buildings,* vol. 87, pp. 211-219, 2015.

[35] U. Eicker, E. Demir and D. Gürlich, "Strategies for cost efficient refurbishment and solar energy integration in European Case Study buildings," *Energy and Buildings,* vol. 102, pp. 237-249, 2015.

[36] PVT Austria, "Anbieter-Homepage," [Online]. Available: https://www.pvtechnologies.at/. [Accessed 2023 03 01].

[37] J. Shen, X. Zhang, T. Yang, L. Tang, H. Shinohara, Y. Wu, H. Wang, S. Pan, J. Wu and P. Xu, "Optimizing the Configuration of a Compact Thermal Façade Module for Solar Renovation Concept in Buildings," *Energy Procedia,* vol. 104, pp. 9-14, 2016.

[38] P. Elguezabal, A. Lopez, J. Blanco and J. Chica, "Assessment on the Efficiency of an Active Solar Thermal Facade: Study of the Effect of Dynamic Parameters and Experimental Analysis When Coupled/Uncoupled to a Heat Pump.," *Energies,* vol. 13, no. 3, p. 597, 2020.

[39] S. Kalogirou, Y. Tripanagnostopoulos and M. Souliotis, "Performance of solar systems employing collectors with colored absorber," *Energy and Buildings,* vol. 37, no. 8, pp. 824-835, 2005.

[40] WAF-FassadensystemeGmbH, "WAF Solar facade," [Online]. Available: https://www.waf.at/solarsysteme/. [Accessed 2023 02 01].

[41] 3S Swiss Solar Solutions AG, "Solarfassade," [Online]. Available: https://www.3s-solar.swiss/3s-solarfassade. [Accessed 2023 02 01].

[42] Schweizer Energie, "Swisspipe," [Online]. Available: https://www.schweizer-energie.ch/. [Accessed 2023 01 01].

[43] TESLA, "Solar roof," [Online]. Available: https://www.tesla.com/de_at/solarroof. [Accessed 2023 01 01].

[44] Energie Solair, "Solar Roof," [Online]. Available: https://solarimpulse.com/companies/energie-solaire-sa. [Accessed 2023 01 01].

[45] G. J. Borràs, C. Lerma, Á. Mas, J. Vercher and E. Gil, "Contribution of green roofs to energy savings in building renovations," *Energy for Sustainable Development,* vol. 71, pp. 212-221, 2022.

[46] R. Pandit and D. N. Laband, "Energy savings from tree shade," *Ecological Economics,* vol. 69, pp. 1324-1329, 2010.

[47] ECKEL ENERGY, "ECKEL ENERGY - Homepage," [Online]. Available: https://eckel-energy.com/. [Accessed 01 02 2023].

[48] A. E. Fenner, V. Zoloedova and C. J. Kibert, "Conference Report 2017: State-of-the-art of Modular Construction," in *Rinker School of Construction Management University of Florida*, Gainesville, 2017.

[49] IEA ECBCS Annex 50, "Prefabricated Systems for Low Energy Renovation of Residential Buildings," [Online]. Available: https://www.nachhaltigwirtschaften.at/resources/iea_pdf/endbericht_201225_iea_ecbcs_annex_50.pdf. [Accessed 2023 02 01].