The PLUG-N-HARVEST Façade: A Second Skin with Active and Passive Components

Verena Dannapfel[1], Tanja Osterhage[2], Maike Klein[2], Rita Streblow[2], Marius Vontein[3], Dirk Müller[2], Markus Kuhnhenne[3]

1 E.ON Energy Research Center, Institute for Energy Efficient Building and Indoor Climate, RWTH Aachen University, Aachen, Germany, email: verena.dannapfel@eonerc.rwth-aachen.de
2 E.ON Energy Research Center, Institute for Energy Efficient Building and Indoor Climate RWTH Aachen University, Aachen, Germany
3 Institute of Steel Construction, Sustainable Metal Building Envelopes, RWTH Aachen University, Aachen, Germany

Abstract

The construction of office buildings in particular, as well as multi-family dwellings, are largely based on regular planning grids, and the widths of such grids appear to be repetitive across Europe.
In the EU project, PLUG-N-HARVEST, a multi-modular façade system for refurbishment, based on these planning grids, is developed. To achieve a comprehensive improvement of the building´s energy efficiency, different solutions for active and passive energy demand reduction, as well as harvesting of heat and power were combined, while also taking into account the existing building structure, climatic region, and usage profile.
The PLUG-N-HARVEST façade is designed to enclose the existing façade like a second skin. Thus, the remaining protection provided by the existing outer shell allows continuous usage. The modular approach enables economic efforts by serial production with a high degree of prefabrication and thus shortened assembly time. At the same time, the toolkit design follows the principles of the circular economy. In visual terms, various façade surfaces will be available to allow both an orientation to the existing building and an aesthetic reorientation.
In 2019, pilot buildings in Greece, Spain, the United King dom, and Germany aim to show the adaptability of the modular toolkit to different façade geometries and to assess its ecological and economic benefits.

Keywords

Refurbishment, Modular, Circular Economy, Renewable Energy Sources (RES), Building Integrated Photovoltaics (BIPV)

DOI 10.7480/jfde.2019.1.2772

1 INTRODUCTION – CHANCES OF A MODULAR TOOLKIT FOR THE REFURBISHMENT OF FAÇADES

Around 75 % of the European building stock is deemed energy inefficient by the European Commission (European Commission, 2016). Buildings are responsible for 38 % of the EU's CO2 emissions and, at 40 %, its largest final energy consumer (European Commission & Joint Research Center, 2015). To meet the EU's energy efficiency targets for 2050, a constant minimum renovation rate of 3 % is required (Europäisches Parlament, 2018). This means that it is necessary to triple the average rate of 1 % in 2011 (BPIE, 2011).

How can refurbishment become more attractive?

The construction of office buildings in particular, as well as multi-family dwellings, are largely based on regular planning grids. Throughout Europe, the widths of grids appear to be repetitive as they are based on the Euromodule or masonry sizes, which are consistent across several countries. The idea of the EU-project PLUG-N-HARVEST is to develop a modular façade toolkit, based on these typical grids. This enables economic advantages by serial production with a high degree of prefabrication and thus shortened assembly time. Moreover, the system is designed for exterior application to face obstacles against refurbishment beyond pure investments, namely the wish to allow the ongoing use of a building during refurbishment (dena, 2017), which is enabled by the remaining protection provided by the existing outer shell.

The project PLUG-N-HARVEST is funded by the European Research and Innovation Programme Horizon 2020 and started in September 2017 with a project duration of 51 months. The international project consortium consists of research, industrial, and local government partners from Germany, Greece, Spain, the United Kingdom, and Romania, while the Greek Centre for Research and Technology Hellas (CERTH) has the leadership. In Germany, a cross-institutional team of the RWTH Aachen University of architects, civil engineers, and mechanical engineers is responsible for the technical and architectural design.

As mentioned before, one potential market for the PLUG-N-HARVEST system can be found in offices. In Germany, 65% of the office building stock was built before 1978 and thus before the implementation of the 1st German Heat Saving Ordinance (dena, 2017). In different European countries, like the United Kingdom, the Netherlands, or Germany, from 1950 to 1970, offices were largely built in skeleton construction or with storey wide ribbon windows (Ebbert, 2010). A typical U-value for mullion-transom-façades and metal windows of this building age can be assumed to 4.3 W/(m^{2}K) (BMU & BMWi, 2015). To put this into perspective: The valid German energy saving ordinance (EnEV) 2014/2016 specifies a maximum U-value for windows of 1.3 W/(m^{2}K). This serves as an indication of the improvement potential in terms of transmission losses. Nevertheless, the central elements of modern office refurbishments are mechanical ventilation, heating, and cooling (dena, 2017). Improvements in the building technology achieve energy as well as life cycle cost savings and increased user comfort. That´s why a central element for the energetic improvement is the thermal conditioning of buildings. In Germany, it accounts for about 27% of the primary energy consumption (dena, 2018).

Façade systems that are entirely passive can achieve final energy savings up to 50% (dena, 2016). Complementary technology, such as decentralised ventilation units with heat recovery, shading systems, or collectors for renewable energies can exploit further saving potentials. The modules of the PLUG-N-HARVEST façade include both passive components, like insulation or windows, and active components for ventilation, heating, and cooling. In addition, the PLUG-N-HARVEST concept can also be transferred to multi-family dwellings, which make up 40 % of the German living space (dena, 2018) and of which, similar to the office sector, about 60 % was built before 1978 (dena, 2018).

The individual modules of the PLUG-N-HARVEST façade, as well as their components, are separately exchangeable, which enables the implementation of a leasing model and supports a further project objective, namely compliance with the principles of the circular economy, by the recyclability of complete modules, components, and materials. Thus, PLUG-N-HARVEST has the potential to overcome existing obstacles to refurbishment, while being economically advantageous to existing solutions.

2 METHODOLOGY – ANALYSIS OF STRUCTURES AND REQUIREMENTS

The RWTH Aachen University is responsible for the modular toolbox design, dynamic simulations, and laboratory testing of the prototypes, as well as the German pilot study. Therefore, civil engineers, mechanical engineers, and architects from the Institute of Steel Construction - Chair of Sustainable Metal Envelopes and the E.ON Energy Research Center - Institute for Energy Efficient Buildings and Indoor Climate, work together in collaboration.

The PLUG-N-HARVEST design concept is based on a constructional analysis of offices and multi-family dwellings in Europe. Office buildings mostly follow country-specific or European standardised horizontal grids. Fig. 1 shows two examples of office buildings with the same horizontal grid, one with ribbon windows and one with a mullion-transom façade, which were typical construction designs between 1950 and 1970 in several countries in Europe (Ebbert, 2010). Due to fall protection regulations, the balustrades are also of similar heights, with a minimum of 90cm. Differences can be found in the storey heights, as they depend on the individual room height, as well as floor and false ceiling constructions. Some residential and office buildings do have vertical projections in the external wall, for example oriels or balconies, which interrupt vertical grids and need to be taken into account in the design.

FIG. 1 Regular horizontal and vertical grids of office buildings

A closer look at European grids shows that they are based either on the Euromodule, which was implemented by ISO 1006 in 1973, or on a country-specific basic module derived from masonry sizes (see Fig. 2). This leads to different extension grids as well as typical façade grids based on workspace regulations. The structural grid can be a multiple of the horizontal façade grid, for example, in skeleton construction.

	Standard	Basic Module [cm]	Extension Grid [cm]	Horizontal Facade Grid [m]	Structural Grid [m]
European Union from 1973	Euromodule ISO 1006	10	60	1.20	7.20
				1.50	7.50
Germany (additional)	Masonry Size DIN 4172	12.5	62.5	1.25	7.50
				1.50	
United Kingdom (additional)	Masonry Size BS 5628	11.25	67.5	1.35	...
…	...	...			

FIG. 2 European basic modules and common grids

In the sector of residential buildings, regular grids are used in many objects, but as shown in Fig. 3, they have divergent measurements for the horizontal and the vertical grids from one object to the other. Only the balustrades remain at a minimum height of 90 cm.

FIG. 3 Regular grids in multi-family dwellings without repetitive measurements

The possibility to assemble an additional façade in front of the existing one is directly related to the existing load-bearing structures and its remaining capacity. Skeleton structures transfer loads horizontally to the primary load-bearing structure, while massive wall constructions are part of the primary structure themselves. Potential fixing points of the primary or secondary load-bearing structure need to be accessible. Therefore, existing external insulation or cladding must be partly removed. For both skeleton and massive construction, fixing to the ceiling construction could be a suitable solution, if its remaining load bearing capacity is sufficient. The energetic quality of buildings can be increased either by the reduction of the final energy demand or by the substitution of fossil fuels by renewable energy sources (see Fig. 4).

As mentioned in the introduction, transmission losses are having a high impact on the energetic demand of a building. A German study shows that improving the quality of windows and external walls achieves a final energy saving of up to 50 % (dena, 2016), and in office buildings in particular, where large areas of the façade have a poor U-value, about three to four times worse than the minimum standard for new buildings, the potential for energy saving is high. Each European country has its own U-value requirements that are in accordance with its climatic region and, usually, additional restrictions for the building´s primary energy demand and emissions. In the Mediterranean climate, for example, the prevention of summerly overheating may have a higher priority than heating.

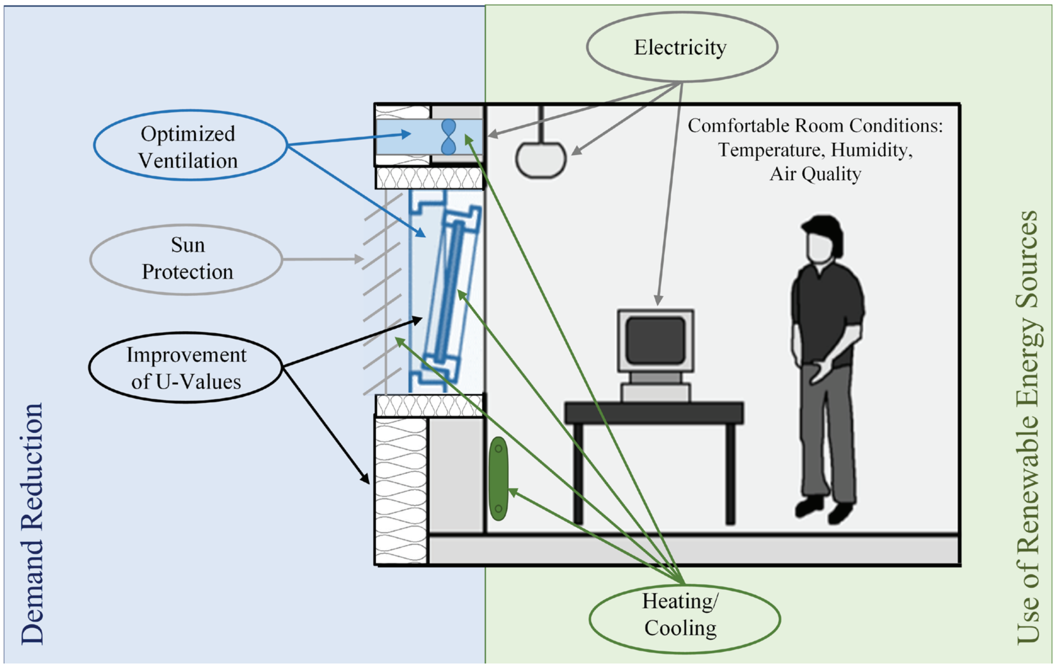


FIG. 4 Improved energetic quality by demand reduction and the use of renewable energy sources

External sun protection is an appropriate measure in this case. Furthermore, optimised ventilation, for example demand-led or with heat recovery, is capable of reducing heat losses, while keeping or increasing the user comfort.

Renewable energy sources can be used to supply electricity or heat. To harvest electricity within a façade, building integrated photovoltaics (BIPV) or building applied photovoltaics (BAPV) are conceivable. Thermal conditioning can be done with the support of solar thermal collectors to provide heated water or air and electrical devices like infrared heaters or cooling units.In terms of aesthetic requirements, non-residential buildings tend to favour modern surfaces, like glass, aluminium, or partly visible technology like PV-cells, while residential buildings tend towards an appearance that is adapted to the surroundings, with subdued and natural colours (white, brown, terracotta) and low reflection. Additionally, local building authorities set guidelines for certain districts.

3 EXPERIMENT / RESEARCH – DEVELOPMENT OF THE PLUG-N-HARVEST MODULAR TOOLKIT

3.1 MAIN ELEMENTS

Fig. 5 shows the main elements of the PLUG-N-HARVEST system. The idea within the PLUG-N-HARVEST design is to use recurrent horizontal grids of offices and multi-family dwellings to determine fixed sizes of modules, which then incorporate passive and active components. Site-measured elements can cover differences in storey heights and additionally function as an installation channel for media supply and control, as well as a fire barrier between storeys. The module's frame is made from aluminium. It has fixing points on the top and on the sides and thus can be installed on horizontal or vertical substructures, which transfer the Main elements of the

PLUG-N-HARVEST system additional loads of the system onto the existing load-bearing structure, or to an additional foundation, with a horizontal locking position only. The use of a substructure is not only due to static reasons. It also enables the separate exchangeability of the modules for technical reasons or because of changes in requirements. Nevertheless, their installation needs to be airtight and secure. So far, within the project, 1.10 m, 1.20 m, and 1.60 m have been fixed as the widths of modules, as well as 90 cm for the height of the balustrade module. Further module heights are based on typical window sizes. The modules' design and choice of components are based on the principles of the circular economy.

In the case of divergent or lacking grids, as typical in small residential buildings, the use of balustrade modules in combination with a conventional façade system opens the possibility to add efficient building technology and energy harvesting components to an existing building with short planning processes and under continuous usage.

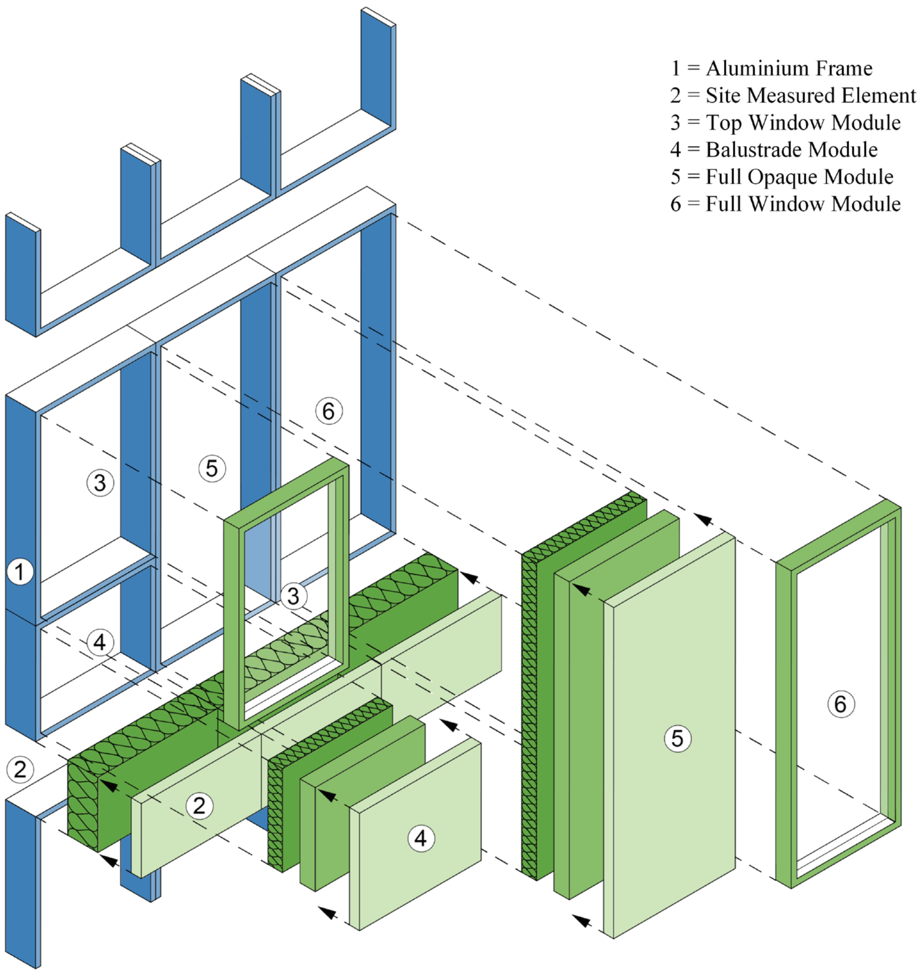


FIG. 5 Main elements of the PLUG-N-HARVEST system

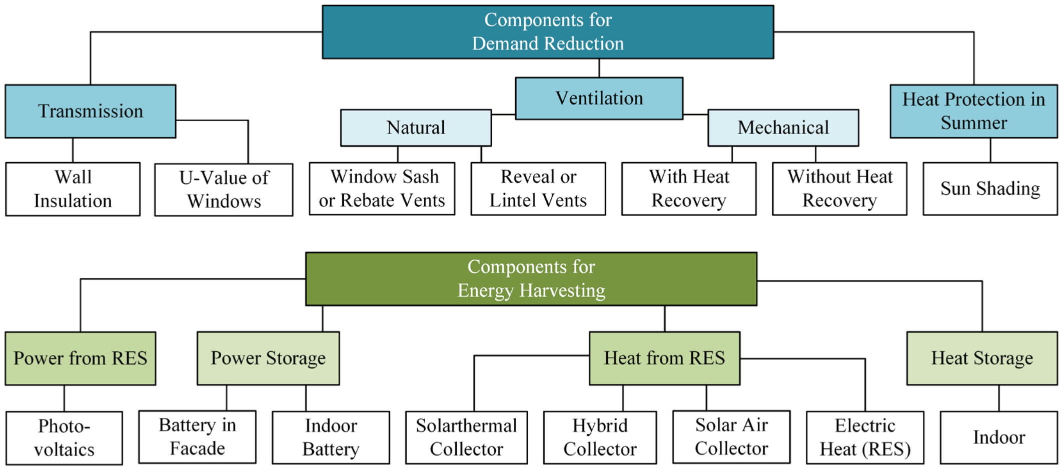


FIG. 6 Components for demand reduction and energy harvesting

3.2 COMPONENTS

As mentioned in Chapter 2, measures to increase the energetic quality of a building can focus on either the demand reduction or the use of renewable energy sources (RES), which shall be provided locally by energy harvesting within PLUG-N-HARVEST. Components from both approaches have been examined. Those which fulfil the technical requirements of security and noise regulations, and which fit inside the determined module sizes, are listed in Fig. 6. Market available products got collected within a database. Their suitability in terms of circular economy is currently under investigation.

The first approach towards the module´s depth is 30 cm. The first step in the choice of components is the determination of the required additional insulation by taking the module´s frames and substructure into account. This leads to an object-specific free space for technical equipment or additional insulation. In the case of further requirements, for primary energy demand for example, these were fulfilled primarily before the client could choose further components based on his personal preferences. All components will remain separately exchangeable in the cases of changes in use, the end of the component´s service life, or the end of a leasing contract. The interaction with the interior is made by drilling holes for media supply, like an air duct with an outlet and heat recovery (HR), and for control purposes as well as through a supplementary connection to the technical room for the potential storage of heat and power or network feeding.

The claddings can be architectural or technical and do partly overlap with the aluminium frame. They need to be easily removable to be exchanged, but also to access the components in behind and the installation duct within the site measured element. Although different cladding types do have different cladding depths, the leading edge of the façade needs to remain in the same position. Therefore, deep claddings are added by using an architectural frame, so they can leap between the profiles of the aluminium frame. The remaining differences between the individual claddings can be covered by adjusted rear ventilation gaps. For the windows, additional or substitutional solutions are conceivable. Furthermore, an option with only a ‘hole’ in front of the existing window will be evaluated. An additional window could be, for example, sliding or opening outwards. Through this approach, the quality of the existing windows is taken into account and therefore, the costs and the embodied energy of the refurbishment can be kept low.

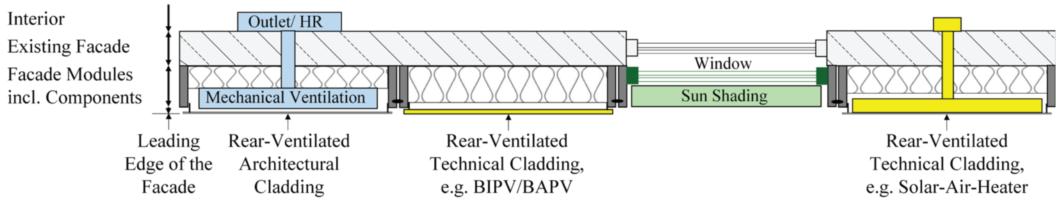


FIG. 7 Examples of different module configurations

During the assembly of the PLUG-N-HARVEST façade, the remaining or subsequent disassembled window protects the interior, so that persistent usage is possible. Each module can be configured from different components, based on country-specific regulations, the existing building´s load-bearing structure and energetic quality, as well as individual preferences in terms of costs, aesthetic appearance, and ecological performance. One example of such a configuration is shown in Fig. 7.
As mentioned before, there are various aesthetic requirements for the appearance of non-residential and residential buildings. While the possibility for purely architectural claddings is well known, technical claddings, like building integrated or building applied photovoltaics (BIPV/ BAPV), also offer manifold surfaces to meet those requirements.

FIG. 8 Modern surfaces with photovoltaics

Fig. 8 shows different modern surfaces with photovoltaic technology in use. There is a huge variety of possible colours and patterns available, as well as prints and coatings. Furthermore, semi-transparent BIPVs with daylight transmission up to 70 % are possible, but will not be focused upon in PLUG-N-HARVEST, as the daylight transmitting areas of existing buildings will not be enlarged by the refurbishment and a reduction of the previous light transmission may lead to problems with workspace regulations and decreased comfort.

Fig. 9 and Fig. 10 show photovoltaic products with more subdued colours and non-reflective to low-reflective surfaces, with the help of structured glass surfaces. These are suitable options for residential buildings in particular, as they have a similar appearance to existing surfaces, like plastering or clinker bricks. The left side of the figures shows residential reality, while the right side shows matching implemented PV-solutions.
However, the aesthetic appearance of photovoltaic products is directly linked to its efficiency and cost. In particular, thin film technologies and crystalline cells with coloured applications are accompanied by reduced efficiency under Standard Test Conditions (Green et al., 2018) and higher system costs (Wietschel, Ullrich, Markewitz, Schulte, & Genoese, 2015). Furthermore, toxic ingredients used in specific technologies like arsenide or cadmium can result in poor ecological performance in the case of circular economy (MCDonough Brangart Design Chemistry, 2016). This is the reason why the choice of a specific type should be considered holistically. This is also the focus in PLUG-N-HARVEST.

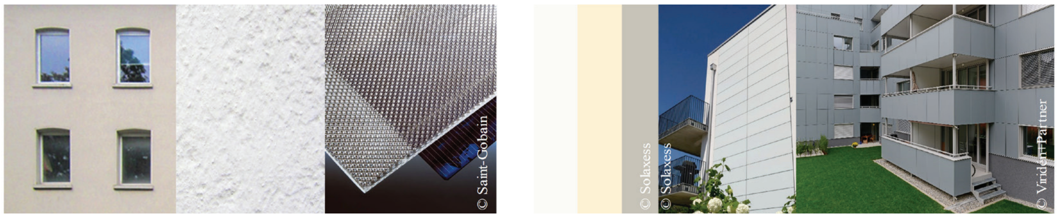


FIG. 9 Photovoltaics with subdued colours, white to grey, and structured glass surfaces for matte appearance

FIG. 10 Photovoltaics with subdued colours, terracotta

4 RESULTS – VALIDATION AND DETAILING OF THE PLUG-N-HARVEST DESIGN

4.1 ARCHITECTURAL AND TECHNICAL DETAILING

At the beginning of 2019, the first prototypes of the PLUG-N-HARVEST system will be realised and examined in the experimental hall of the Institute for Energy Efficient Buildings and Indoor Climate of the RWTH Aachen University; these focus on the constructional details of the modules themselves. Firstly, the design has to be durable and secure, in terms of the stability of the modules as well as the secure fixing of the cladding on them. The fixing needs to resist static and dynamic forces and at the same time must be easily removable for exchange and maintenance of the technical units behind. Secondly, based on the fixed module sizes, the total façade system has to be capable of handling the constructional tolerances. In the vertical direction, these will be covered by the site measured element. In the horizontal direction, the junction between the modules needs to be tolerance-adaptive while at the same time it has to fulfil tightness requirements against wind and rain, as well as after the exchange of a module. Thirdly, movements of the modules caused by temperature and deflection will occur and need to be compensated to avoid rising tensions. In terms of building physics, the prevention of thermal bridges and condensation are the main tasks.

Fig. 11 shows sketches of the PLUG-N-HARVEST design and examples of the current constructional and physical building issues under examination. The laboratory testing on the prototypes will focus on those subjects with the aim to validate or adjust the design concept.

Besides the physical tests, dynamic simulations in Modelica®, as well as CFD (Computational Fluid Dynamics)-simulations, are conducted to prove required ventilation and thermal behaviour. Keeping the project goal of conformity with the principles of circular economy in mind, the design is also examined under their guidelines for separation and selection of materials.

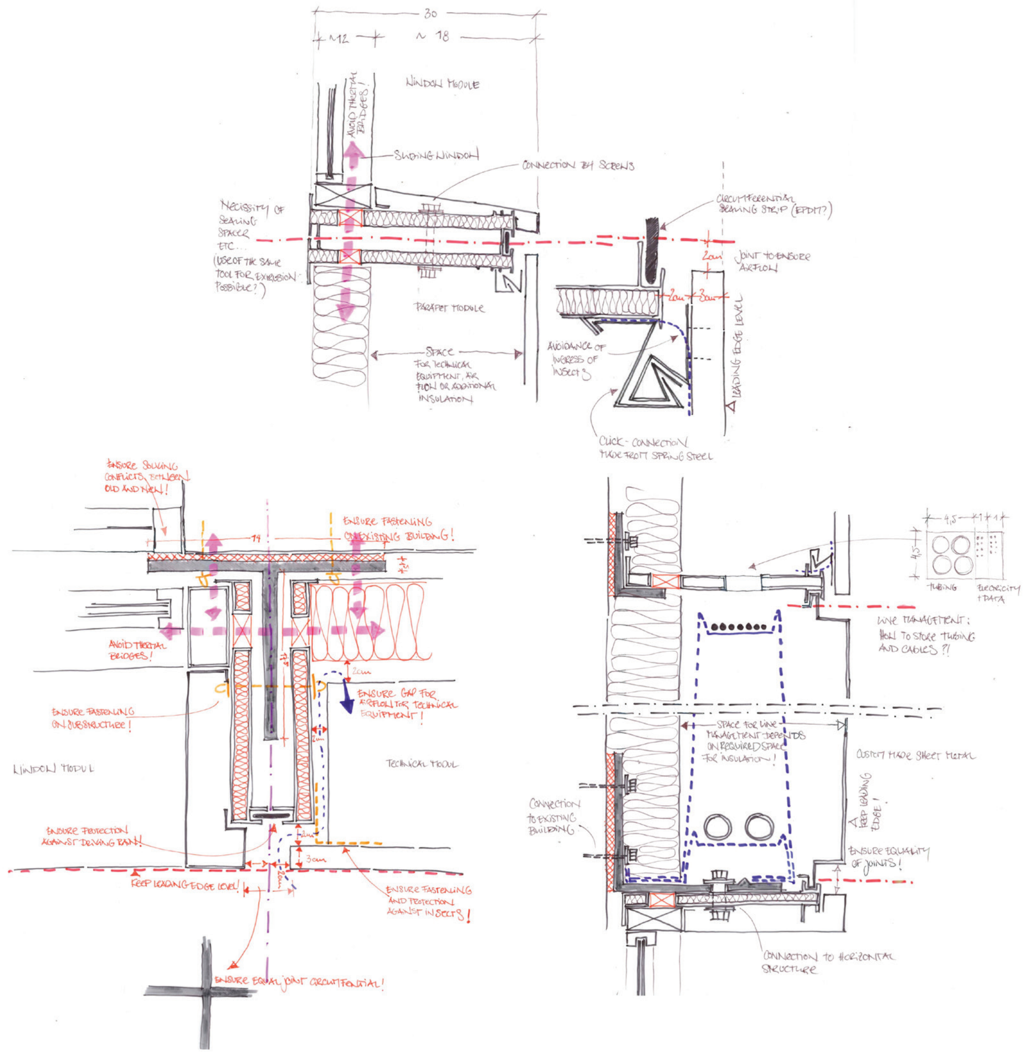


FIG. 11 Sketches and current issues in design details

4.2 SUITABLE BUILDINGS AND SUBSTRUCTURES

The PLUG-N-HARVEST modules are suitable to be fixed to either a horizontal or a vertical substructure, which itself will transfer forces created by the façade extension to the existing load-bearing structure or, if necessary and possible, partly to an additional foundation. The horizontal substructure will be realised by an L-angle and the vertical by a T-profile. In accordance with the modular approach, both substructures' dimensions have been calculated for different combinations of module width or, respectively, static lengths as multiples of these, as well as storey heights, a maximum additional weight of 150 kg/m^2, and deflection limited to l/300. Table 1 shows an extraction of this calculation for the horizontal L-angle.

Furthermore, different qualities and heights of concrete ceilings have been examined in terms of their capability to transfer the resulting forces. The calculation is made for a direct application with dowels and two screws per module into the core area of the ceiling. The resulting minimal thickness for the ceiling can also be found in Table 1. The table shows that certain ceilings of either insufficient concrete quality or insufficient thickness will not be able to hold the substructure with the attached modules under these boundary conditions. Smaller thicknesses may be possible using more fixation points per module or optimised weight. These options will be examined further over the course of the project. Because the ceiling, as a load-bearing structure of secondary order, works as a load-transferring element, its total capability also has to be approved in accordance with further parameters such as traffic loads. Moreover, the further transfer via the primary structure – pillars or walls – and the foundation to the ground cannot be analysed within the modular toolkit framework and must be proven for each object by an authorised local engineer.

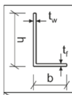
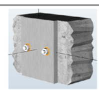
 b x h x t_w [mm]	Dimension of Horizontal Substructure (L-Angle) in accordance to Module Widths „A“ = 1.10 m and „B“ = 1.20 m and limited deflection of l/300					
Static Length / Storey Height	3 x Module Width		5 x Module Width		7 x Module Width	
	„A“	„B“	„A“	„B“	„A“	„B“
3.00 m	150 x 200 x 10	150 x 200 x 10	200 x 200 x 12	250 x 200 x 12	300 x 200 x 12	300 x 200 x 12
3.50 m	150 x 200 x 10	150 x 200 x 10	200 x 200 x 12	250 x 200 x 12	300 x 200 x 12	300 x 200 x 15
4.00 m	150 x 200 x 10	150 x 200 x 10	250 x 200 x 12	250 x 200 x 12	300 x 200 x 15	350 x 200 x 15
	Minimal Thickness of Existing Concrete Ceilings for the Application of Substructure by Dowels in accordance to Module Widths „A“ = 1.10 m and „B“ = 1.20 m, Module Weight ≤ 150 kg/m²					
Concrete Quality / Storey Height	C 20/25		C 25/30		C 30/37	
	„A“	„B“	„A“	„B“	„A“	„B“
3.00 m	22 cm	22 cm	22 cm	22 cm	20 cm	20 cm
3.50 m	22 cm	> 24 cm	24 cm	24 cm	22 cm	24 cm
4.00 m	> 24 cm	> 24 cm	24 cm	> 24 cm	24 cm	24 cm

TABLE 1 Substructure dimensioning

4.3 APPLICATION EXAMPLES

The PLUG-N-HARVEST modular toolkit can be applied to different types of buildings, which are based on a regular planning grid. Not all grid sizes will be covered by the final toolkit, but the selection will follow a potential analysis and economic criteria. Different application examples are displayed in Fig. 12. The first building shows the Civil Engineers' Building of RWTH Aachen University, where the Institute of Steel Construction, a member of the PLUG-N-HARVEST team, is situated. In the visualised module arrangement the following module sizes were used: Balustrade Module 1.35 m x 0.90 m, Top Window Module 1.35 m x 2.00 m. The second building is the German pilot, an office building in Aachen, with a Balustrade Module of 1.20 m x 0.90 m, Top Window Module of 1.20 m x 1.70 m, and a Full Opaque Module of 1.20 m x 2.50 m. The last building shows the Spanish pilot, a social housing complex near Barcelona, for which the following modules and sizes are used: Balustrade Module of 1.20 m x 0.90 m, Top Window Module of 1.20 m x 1.30 m, Full Opaque Module of 1.60 m x 2.20 m, and a Full Window Module of 1.20 m x 2.20 m.

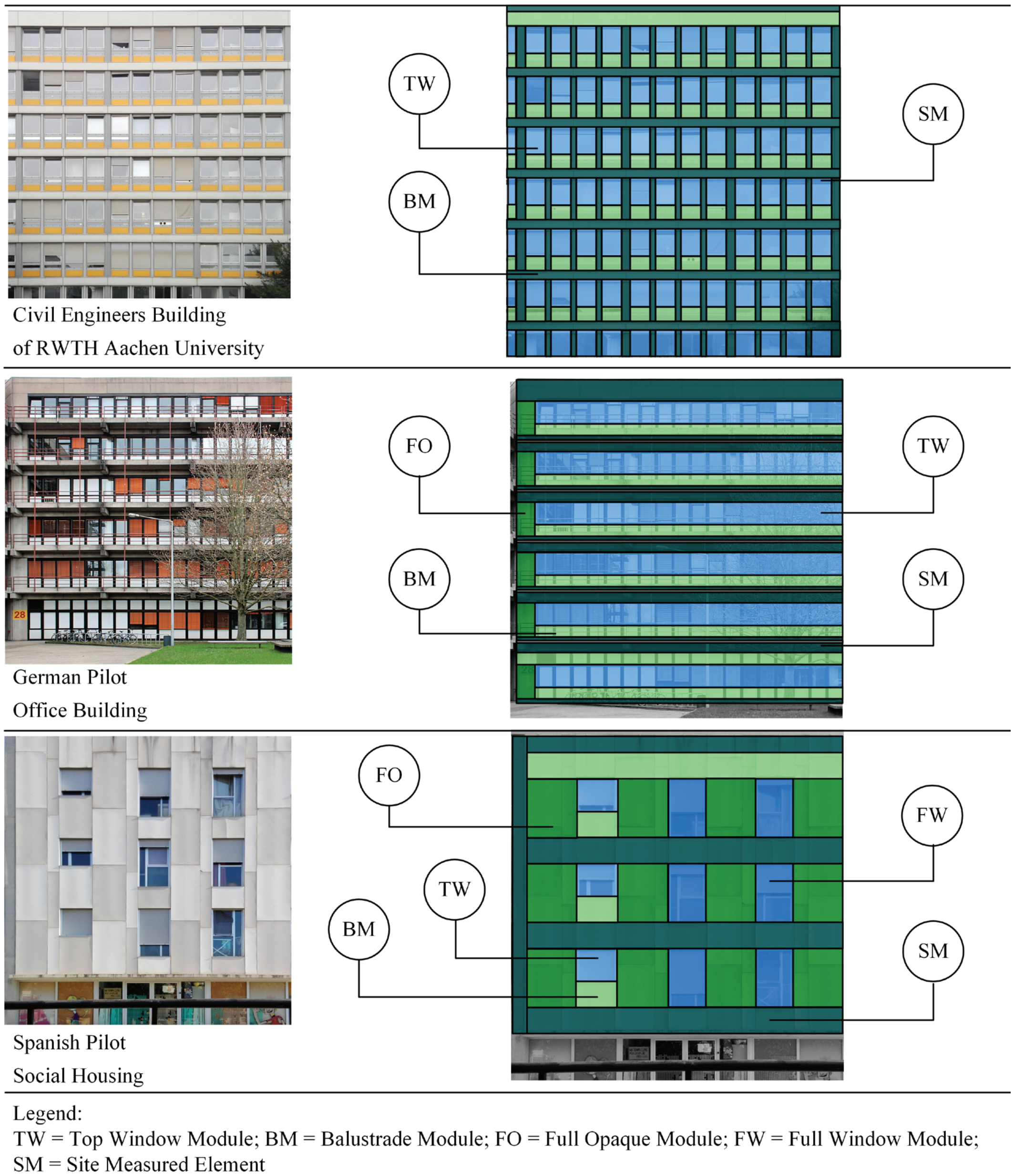


FIG. 12 Application examples for different building types

The implementation of the PLUG-N-HARVEST system at the aforementioned pilots in Germany and Spain and additional residential buildings and offices in Greece and Wales is planned for 2019.
The pilot tests will be accompanied by a process of monitoring to examine the building´s behaviour, energy demand and supply by energy harvesting, interior comfort, and user satisfaction, before and after the refurbishment. The choice of suitable components including technical equipment, is based on a configuration flowchart, in which country-specific regulations, existing building structures, and energetic quality, as well as personal preferences, are taken into account. The modular approach and the external installation result in high requirements for the installation paths and interfaces. In the same context, a plug-n-play automation, which is able to interoperate with different devices inside the PLUG-N-HARVEST system, as well as existing technology and sensors within the building, is currently under development.

5 CONCLUSIONS – ADVANTAGES OF THE PLUG-N-HARVEST MODULAR TOOLKIT

The PLUG-N-HARVEST concept is a multi-modular toolkit for the refurbishment of the European building stock. It is intended to overcome existing obstacles to refurbishment, such as high investments and temporary vacancy, through large scale production and exterior implementation in front of the existing façade. The combination of components for the reduction of active and passive energy demand and those for renewable energy harvesting enables a comprehensive improvement of the building´s energetic quality. At the same time, the design follows the principles of circular economy.

The modular approach has the potential to be economically and ecologically advantageous to existing refurbishment solutions under the preliminary condition that a refurbishment object fits to the system´s boundary conditions. Such conditions include, on the one hand, a regular planning grid, which matches one or more of the module sizes that are determined at the end of the project and, on the other hand, the remaining capacity of the existing building´s load-bearing structure or the possibility to add a foundation to capture the additional weight of the PLUG-N-HARVEST façade. Especially in the office and multi-family dwellings sector, the PLUG-N-HARVEST system might be an appropriate solution to be introduced at a large-scale.

Though the use of fixed module sizes and their ability to remain separately exchangeable has economic and ecological advantages, it also comes with challenges from a technical perspective, for example, the covering of tolerances or the junction details between the modules and the cladding. Within PLUG-N-HARVEST, suitable solutions to the challenges are developed.

PLUG-N-HARVEST will provide a methodology by which modules can be individually configured based on country-specific requirements for construction and energetic refurbishment, such as U-value requirements, primary energy demand or emissions, object-specific boundary conditions, and an overview of available components set up as product-neutral technology profiles.

Pilot projects in Greece, Spain, the United Kingdom, and Germany will be used to validate the technical implementation of the PLUG-N-HARVEST concept and to assess its ecological and economic benefits. The development of a business plan and the identification of potential exploitation partners complete the approach.

Acknowledgements

We are thankful for the kind permission to use pictures of:
Issol sa/nv, Dison (Liège), Belgium, Products Issol Solar-Terra and Cenit Visual, http://www.issol.eu
Avancis GmbH, Torgau, Germany, Product Avancis Powermax Skala, Project Sennareal, Bern, www.avancis.de
Polysolar Ltd., Cambridge, United Kingdom, PS-A and PS-CT-series, www.polysolar.co.uk
Compagnie de Saint-Gobain, Courbevoie, France, Product SGG Albarino S, www.saint-gobain.com
Solaxess SA, Neuchâtel, Switzerland, White Photovoltaics at the refurbishment project Boudry, Switzerland, www.solaxess.ch
Viridén+Partner AG, Zurich, Switzerland, BFE Lighthouse project MFH Hofwiesen-/Rothstrasse in Zurich, refurbishment and spatial extension with an active solar façade (BIPV) from coloured photovoltaic modules with monocrystalline cells, www.viriden-partner.ch

© European Union

This project has received funding from the European Union´s Horizon 2020 research and innovation programme under grant agreement No 768735.

References

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, & Bundesministerium für Wirtschaft und Energie. (2015). Bekanntmachung der Regeln zur Datenaufnahme und Datenverwendung im Wohngebäudebestand [Publication of rules on data collection and use in the residential building stock].Berlin.

Ebbert, T. (2010). Re-Face: Refurbishment strategies for the technical improvement of office façades. (Doctoral dissertation). Delft: Technische Universiteit Delft.

Deutsche Energie-Agentur GmbH. (2017). Büroimmobilien: Energetischer Zustand und Anreize zur Steigerung der Energieeffizienz [Office properties: Energy status and incentives to increase energy efficiency]. Berlin.

MCDonough Brangart Design Chemistry. (2016). C2CCertified Product Standard V3.1. Charlottesville,Virginia.

Wietschel, M., Ullrich, S., Markewitz, P., Schulte, F., & Genoese, F. (2015). Energietechnologien der Zukunft [Energy technologies of the future]. Wiesbaden: Springer Fachmedien Wiesbaden.

Green, M. A., Hishikawa, Y., Dunlop, E. D., Levi, D. H., Hohl-Ebinger, J., & Ho-Baillie, A. W.Y. (2018). Solar cell efficiency tables (version 51). Progress in Photovoltaics: Research and Applications, 26, 3-12. Retrieved from https://doi.org/10.1002/pip.2978

Europäisches Parlament. (2018). Gesamtenergieeffizienz von Gebäuden [Energy performance of buildings]. Brussels.

European Commission, & Joint Research Center. (2015). Energy Renovation: The Trump Card for the New Start for Europe. Brussels.

European Commission. (2016). Accelerating clean energy in buildings: Clean Energy For All Europeans. Brussels.

Deutsche Energie-Agentur GmbH. (2016). dena-Studie: Auswertung von Verbrauchskennwerten energieeffizienter Wohngebäude. Berlin.

Deutsche Energie-Agentur GmbH. (2018). dena-Gebäudereport kompakt 2018: Statistiken und Analysen zur Energieeffizienz im Gebäudebestand [dena building report compact 2018: Statistics and analyses on energy efficiency in existing buildings]. Berlin.

Buildings Performance Institute Europe. (2011). Europe´s buildings under the microscope: A country-by-country review of the energy performance of buildings. Brussels.

COPYRIGHT NOTICE

Author(s) hold their copyright without restrictions.