The Future of Solar Integration: Towards Efficiency in Solar Design through Aesthetics, Optimisation and Customisability

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Abstract

The efficient integration of Building Integrated Photovoltaic and Solar Thermal systems (BIPV/T) within an increasingly dense urban fabric requires both technical optimisation and qualitative, formal innovation. However, the latter is often overlooked in technological developments; current BIPV/T systems discourage a widespread implementation by stakeholders as these systems are perceived of having a poor formal quality. The aim of this paper is therefore to provide a new perspective for the development of the solar industry. Following a Research through Design methodology, this approach is examined firstly through the design and construction of a prototype unit, and secondly by a thermal and electrical evaluation of the solar design. The prototype unit, featuring a coloured solar facade with customised photovoltaic and thermal collectors, participated in the Solar Decathlon Europe 21/22 in Wuppertal, Germany.

The key finding is that BIPV/T systems ought to be considered as design elements or architectural building blocks rather than optimised technological systems. This holistic perspective to solar integration resulted from the essential collaboration between architect and engineer. In this way the formal potential of solar design within its production limitations is explored while meeting the technical requirements. Even more, solar design can be used to reach social objectives, as demonstrated in the prototype unit. The full potential of solar integration is, however, to be explored further. The formulated perspective can stimulate an alternative direction for both engineers and designers of the solar industry to work towards a net-zero built environment.

Keywords: Solar Design, Building Integrated Photovoltaic Thermal Systems, Architectural Integration, Energy-Efficiency

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1. Introduction

The imperative of climate change demands an accelerated transition towards renewable energy sources. To transit towards a sustainable energy system a mix of different renewable energy sources is needed (IEA, 2021; IPCC, 2022). In this mix solar power plants play an important role as peak load operators (Bhattacharyya, 2011). There used to be a primary focus on substantial solar fields subsidised by governments and companies, however, there is currently a tendency towards decentralisation and smaller, local application of solar energy involving the current building stock (Ng et al., 2022). This resulted from both the competition of rural space necessary for agriculture and natural environments, and an increasing awareness of sustainability combined with policy implementations allowing for a monetary benefit for residents to adopt solar panels (Bahaj & James, 2007; Vasseur & Kemp, 2015). Simultaneously, it is expected that 68% of people worldwide will live in urban areas by 2050 compared to the current 55% (United Nations, 2018) and, therefore, space will become even scarcer, leading to an increased focus on Building Integrated Photovoltaic and Solar Thermal systems (BIPV and BIST; from here on abbreviated as BIPV/T). BIPV/T can be defined as a system which "makes use of the building envelope for solar energy collection to produce both electrical and thermal energy, providing an efficient way of reducing building energy consumption" (Yang & Athienitis, 2016, p. 887). BIPV/T is currently mainly adopted on building roofs even though facades contain larger available surfaces, thus providing a further opportunity for the implementation of solar design. This facade generation is, however, not yet inherently part of the current toolbox for both newly built houses and renovated dwellings. This is among others due to economic difficulties, critical regulatory issues, and problems regarding grid interaction (D'Ambrosio et al., 2021). Current focus lies on the technological and economic optimalisation of solar design, especially on circularity, grid interaction, and efficiency of vertical solar cells.

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Parallel to these quantitative advancements, the typo-morphological characteristics and the architectural integrability of BIPV/T are also considered a barrier for a greater rate of adoption (D'Ambrosio et al., 2021; Munari Probst & Roecker, 2007). BIPV/T is increasingly implemented in facade design and require a higher delicacy in formal qualities (Frattolillo et al., 2020). Since the facade of buildings determine the public face of the city, BIPV/T cannot be simply considered as technological additions but should be recognised as integral parts of its urban architecture (Munari Probst et al., 2004). The current BIPV/T catalogues contain only a limited selection of variations available for stakeholders while the building stock consists of a vast diversity of appearances. Residents and architects wish not to be limited by sustainable design and implementation of solar generation, but rather they aim for a perpetual improvement of their environment (Alipour et al., 2021; Heinstein et al., 2013). Therefore, technological advancement is no longer the only issue to increase the rate of adoption of solar design: efficiency in deployment can be intensified through aesthetics, optimalisation and customisability.

However, this pathway of future solar integration through aesthetic improvements should not become an excuse to limit the technological optimalisation of solar energy production. The planetary boundaries demand engineers and architects to fundamentally consider the limited resources, the tremendous carbon footprint of PV production and the risks of grid overload (Finnegan et al., 2018; Kabir et al., 2018). The focus should therefore lie both on architectural integrability and on technological optimalisation through solar orientation, preferred solar angle, peak usage of appliances, and limitations provided by BIPV/T production. The authors consider this holistic perspective as a fundamental priority to reach a net-zero built environment.

Current research around solar power generation is focused mainly on the technological testing and optimising of solar systems, on the reduction of costs and on the possibilities of recycling photovoltaic panels after the end of their lifespan (Yang, 2015). Regarding BIPV/T, Maghrabie et al. (2021) have dedicated initial research to outline the development of BIPV/T products and materials. According to the authors, economic and technological innovation are accompanied by a growing interest in the "increasing possibilities of the aesthetics of the BIPV systems" (Maghrabie et al., 2021, p. 17). Munari Probst & Roecker (2007) have set up a range of guidelines for the optimal integration of solar thermal design through several interviews and an additional survey with engineers and architects to ensure both architectural integrability and energy efficiency. In short, these guidelines illustrate the need for 1) using solar energy systems as construction elements, 2) implementing BIPV/T in the general building concept, 3) the ability to choose colours, materials, module size and shape of BIPV/T panels based on the building's material textures (Munari Probst & Roecker, 2007).

Furthermore, Attoye et al. (2018) focused on defining the barriers of adopting BIPV/T and analysing the necessary market tools to elude these barriers. Similar to Munari Probst & Roecker (2007), they mention the urgent need for collaboration between stakeholders such as architects, engineers and solar system companies. Moreover, the need for demonstration products is mentioned in which BIPV/T is seamlessly integrated and which can be used to educate the general public on environmental issues and energy use. It is also stated that BIPV/T products should allow to be customisable. This connects to the vision of Douglass (2008) on how any sustainable architectural innovation requires the design to be 'universally specific', meaning that every architectural innovation aiming for sustainability should have a universal concept that can be specified to the demands and needs of different geographical situations and local environmental conditions (Douglass, 2008). Lastly, the conventional solar energy peak could be optimised by flattening the peak distribution and combining it with demand side management (Saffari et al., 2018). This can simultaneously enhance the awareness by residents of solar generation and consumption.

To recapitulate, forementioned research mainly focuses on either the optimisation of solar systems or the theoretical integrability of solar designs within architecture. Combining these two aspects into a 'universally specific' physical prototype would allow for a niche area of research around BIPV/T. This can be further complemented by following the guidelines of Munari Probst & Roecker (2007) while simultaneously aiming to decrease the barriers of BIPV/T adoption as indicated by Attoye et al. (2018). In addition, the demand side management is to be researched concurrently. This paper therefore aims to increase the efficiency of an integrated solar design by researching the possibilities in aesthetics, optimisation and customisation in a holistic manner. A mixed methods approach is utilised in which the design and construction of a physical prototype unit is combined with a thermal and electrical evaluation. Subsequently, the architectural integrability and technical potential of BIPV/T are evaluated and improved guidelines for a holistic integrability are outlined to increase the rate of adoption of solar design within the built environment.

2. Methodology

2.1 Context of the project

Adhering to a Research through Design methodology, the approach of the paper is to evaluate integrated solar design through a realised project named ‘ripple’, which participated in the Solar Decathlon Europe (SDE) competition 21/22 in Wuppertal, Germany. The SDE 21/22 was an international student team competition where fifteen teams from ten countries participated with innovative ideas for energy-efficient, sustainable and socially responsible design (Solar Decathlon Europe, 2022). ‘Ripple’ is designed by Team VIRTUe, a student team from Eindhoven University of Technology (VIRTUe, 2022). The concept ripple is inspired by the ripple effect, where small actions leads to large effects. Starting in 2019, the project was under development for three years and has been realised with a fully built and operational house prototype unit which is named ‘ripple demonstration unit’ (RDU). The RDU was firstly constructed at the Eindhoven University of Technology for testing and optimalisation. Later, the prototype was demounted and built for a second time at the SDE Competition in Wuppertal.

A mixed methods approach is used which combines the design and construction of the prototype unit (RDU) with a qualitative and quantitative evaluation. In the RDU a facade with BIPV/T is constructed and tested as a demonstration of future adoption of solar technology. The RDU was a result of a close collaboration between students of engineering and architecture, academics and companies in the context of a multidisciplinary team. These aspects will be evaluated in the paper with a reflection on architectural integrability and potential for an efficient near future adoption. Additionally, measured results from the RDU will be presented to confirm the feasibility of the proposed design and evaluate the performance of the BIPV/T system. Finally, all results are incorporated into a set of guidelines that aim to increase the efficiency of deployment of solar design.

2.2 Architectural design and construction

The RDU is designed as a universal concept that is scalable to cities in similar climates, however, the elements could be adapted to local environmental conditions and different architectural contexts. The RDU is part of a larger design in which the renovation and addition of storeys is applied to an existing commercial building in Wuppertal. The model in figure 1 on the left shows the Building Design of the renovation and addition of storeys in Wuppertal and the picture on the right shows the RDU during test-building.

Fig. 1: The relation between the Building Design and the RDU. On the left, a model of the Building Design in Wuppertal. On the right, a picture of the RDU after test-building.

The challenge of designing in an urban context with limited space resulted into the idea to integrate Photovoltaic (PV) panels in the building envelope through the design of a solar facade. The starting point for the solar concept was to integrate it into the building concept from the first phase of the design to create an architectural unity and a clear logic that is fitting to the building its surroundings. Consequently, the solar facade is treated as an integrated part of the design and not as a technological addition in the final design stage. The building concept is based on a tessellating pattern that can be repeated as it is built up from rotatable and stackable units. By the selection of a distinctive shape a higher degree of diversity and complexity can be achieved in the created spaces in contrast to the conventionally used rectangle. This yields a spatial variety in the design that is more intriguing and generates more specific rooms and atmospheres inside as well as the outside of the building. This building concept resulted in a specific exterior shape to which the solar panel design needs to relate. The approach was to enhance the exterior shape of the building by altering the shape of the solar panels in a logical way that was fitting to the building concept. Therefore, the solar panel design avoids the accustomed rectangular shape and in contrary consists of glass panels with different angles laminated with PV cells, made possible by the ColourBlast technology (KameleonSolar). The technology allows the creation of coloured solar panels suitable for facade application with a wide-reaching range of available colours.

The placement of the panels along the facade was based on an optimal fit to the building concept in combination with optimisation of the BIPV/T energy generation. The optimal angle for the tilt in PV panels on the roof was identified through simulation study to be 20° for the competition period of June in Wuppertal. The facade, however, presents a 90° surface. Therefore, the optimal combination was found in application of PV panels in the shape of a solar belt that wraps around the roof edge of the facade, where the PV panel angle changes from 90° in the facade to 20° in the roof edge. The detail drawing of the solar belt is presented in figure 2. To prevent shade on these panels, glass railings were selected to minimize the blocking of sunlight by the railing.

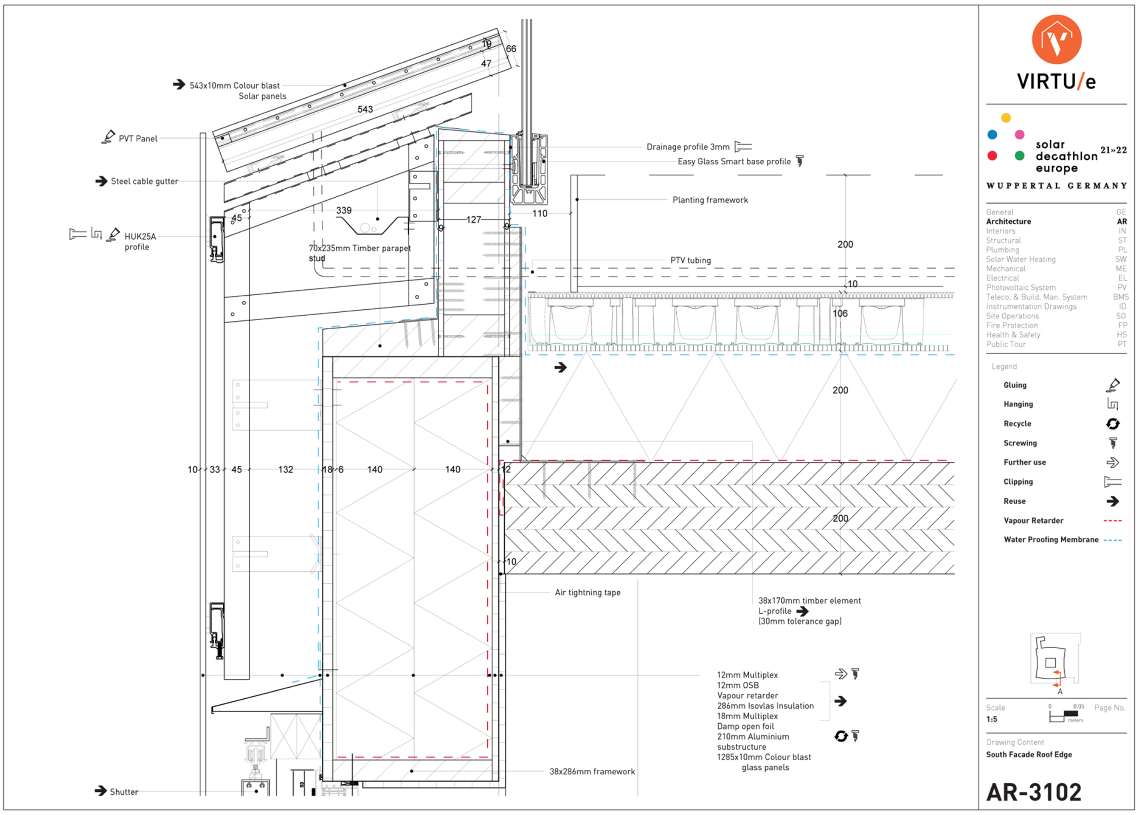

Fig. 2: A detail drawing of the solar belt of the RDU. It shows the tilted PVT panel in the roof edge and the glass railings.

In the facades, the placement of panels was furthermore dependent on the orientation of the facade. The building is built on a -15° orientation. From simulation studies it is found that the west facade would be the most optimal for vertical PV panels, so it was almost fully clad in BIPV/T. The amount of surface area covered by BIPV/T gradually decreased in the design subsequently for the south, east and north facade. The north facade featured no solar panels and the shape of the roof edge was continued with nesting boxes for sparrows and bats made from timber cladding.

2.3 System design

2.3.1 Energy generation

The BIPV/T system of the prototype house is composed of PV modules and a solar collector on the roof, as well as a PVT system integrated into the facade (figure 3). The electrical energy is generated by PV modules integrated in the roof and parts of the facade. In total, seventeen PV modules are installed, and the system has a capacity of approximately 3 kWp, which was the maximum that was allowed by the Rules and Regulations of the SDE competition. Because of this limitation, the position with the highest energy generation potential throughout the day was selected for the equipment of the PV modules. Five conventional crystalline silicon (c-Si) modules, with a capacity of 1825 Wp, are placed on the roof. Twelve coloured PV modules (1152 Wp) are installed along the solar belt (tilted upper section of the facade), which include microinverters. The average efficiency of the coloured PV cells was measured as 16.7% under standard test conditions. The tilt of the PV modules (20°) was optimised using a simulation study to maximise the energy generation potential in the month of June in Wuppertal, Germany. The intention of placing the PV modules at different orientations was to potentially increase the generation of energy in the late afternoon and create a more balanced profile of energy production throughout the day.

In addition to electrical energy, thermal energy is produced in the prototype house by means of a solar-assisted heat pump to heat water for Domestic Hot Water (DHW) and the floor heating. The coloured PV modules of the solar belt are part of a PVT system, with the thermal loop consisting of tubing behind the PV modules that is connected to the heat pump. In addition, thermal energy is captured using a solar collector (1.6 m2) on the roof. The water heated by the solar collector is stored in a tank that is also connected to the heat pump. Due to the water being preheated by the solar collector and the PVT system, the heat pump would possibly need less power to operate. Additionally, hot-fill appliances have been installed – the washing machine and dishwasher make use of water preheated by the solar thermal systems, potentially decreasing their energy demand.

2.3.2. Energy storage

Two 1.2 kWh batteries are used for electrical energy storage (total size of the storage 2.4 kWh). Thermal storage concerns the solar boiler buffer tank of 120 L and a 176 L water storage integrated in the water/water heat pump.

2.3.3. Demand side management

Demand side management has been incorporated in the design of the RDU. By closely monitoring the energy consumption and production patterns and by managing the energy storage systems, the energy management system can decide when building systems and appliances should be using their energy in order reach the lowest amount of carbon emissions while keeping the energy grid balanced. In order to do this, the system gathers data from the local weather forecasts, PV system, battery and power meters. It then creates an approximation of the buildings' energy production and consumption patterns over the following 48 hours. Every suitable building system and appliance is then scheduled and remotely turned on at a certain timeslot which helps in balancing the energy consumption. A prototype of the software that manages and optimises the energy system, capable of working fully autonomously, was demonstrated in the SDE competition.

The energy management system shares data with a physical interface that enables building occupants to interact with the building's energy system. Through a circular interface which consists of a circular LCD screen and a rotary button, it acts as the central energy hub where data about the building's energy consumption, production and storage levels are visualized (figure 4). This visualization informs inhabitants about the conditions outside of the building but also helps them to reflect on their own energy consumption behaviour inside of the home. The occupants can access their personal schedules where devices and systems are turned on in order to reach an energy pattern with higher self-consumption. An overview of all the schedules is also shown throughout a 24-hour timeline. This timeline visualizes when low-carbon energy is in abundance or when it is not.

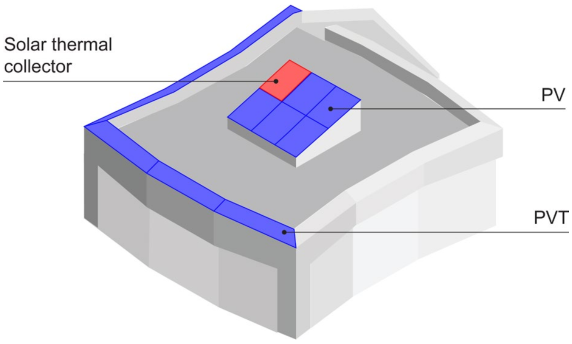

Fig. 3: The BIPV(T) system.

Fig. 4: The interface of the energy management system

2.4 Performance evaluation of the solar design

The performance of the BIPV(T) system with the energy management is evaluated based on the self-consumption index and the overall energy balance. The self-consumption index (eq. 1) describes the proportion of generated energy that is used in the building instead of being fed into the grid:

$$I_{SC} = \frac{E_G - E_F}{E_G} \quad \text{(eq. 1)}$$

in which I_{sc} represents the self-consumption index; E_G is the electrical energy that is generated on site (kWh) and E_F represents the electrical energy which is feed into the electricity grid (kWh) (SDE, 2020).

The measurements were taken during a 10-day period by members of the monitoring team of the SDE, according to the competition rules (SDE, 2020). Various tasks such as running the washing machine or cooking using the oven were performed each day to account for energy consumption.

The energy balance gives an overview of the difference between the total generated and consumed energy during the measurement period. The self-consumption reflects the influence of the solar design, the energy management strategy and the use of solar thermal systems combined with hot-fill appliances for heating water.

3. Results

3.1 Architectural integration

In this chapter, the results from the design and construction of the RDU will be presented in the relation to the BIPV/T design that was created. During the design, the guidelines of Probst et al. (2007) were reflected in the design process. The BIPV/T system has been integrated in a way that it is considered a building element along with the timber cladding, shutters and windows in the facade. By specifying the colour, shape and size of the BIPV/T panels, the solar design has become part of the general building concept of ripple, which will be explained in this chapter.

The shape of the panels was determined by the shape of the building. To make it economically feasible, the choice was made to apply the angle only on one side of the PV panel. The choice for adapting a single angle made it possible to design the strings of PV cells in the same way for each panel, decreasing the production time between different shaped panels as was noted by the manufacturer (KameleonSolar). Therefore, the PV cells are the same for each panel, but the glass shape is different (figure 5), which has no effect on production time hence it is an automized process with 3D laser-cutting technology. Through the scalability concept that is part of ripple in its universal application, the BIPV/T concept can be applied at larger contexts, where different PV panel shapes can be realised without a necessary increase in manufacturing time.

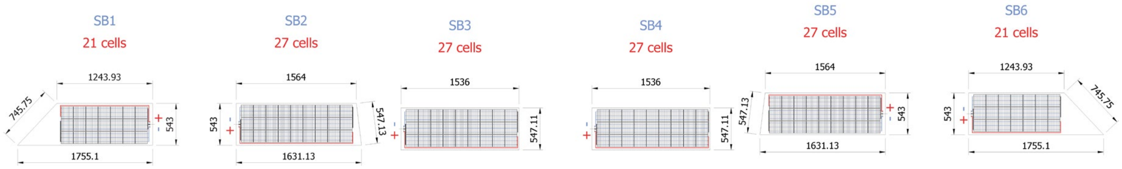

Fig. 5: Example of the BIPV/T panels that were manufactured for the RDU. One side features a different angle for different panels and the opposing rectangular side was used as a reference line to place the PV cells in the same way for all panels.

By rotating the panels corresponding to the design of the facade, the angles could be applied in different directions, allowing the designers to strengthen the building concept with concave and convex facades. In the concave facades (east and west) the solar panels have a tapered shape to become smaller in the middle segment of the facade, where in the convex facades (south and north) the panels have the same shape but become larger instead. The use of both concave and convex facades enhances the visual strength of the effect that is created by the slightly angular walls. When viewed from the corner, as shown in figure 6, this creates a wave-like image that resonates with the overall concept of ripple.

Fig. 6: A picture of the RDU during test-building in July 2021 at the campus of the Eindhoven University of technology.

The coloured PV panels are created by digitally printing a pixelated pattern on the glass, which creates an illusion of a homogenous colour on a distance larger than five metres. The selection of the colour of the panels was made through a careful analysis of the urban context in Wuppertal together with the adjacent material use in the facade. The latter consists of recycled pinewood cladding in two finishings and anodic black powder coated aluminium window frames. The final colour that was selected, a medium taupe colour, was chosen as a fitting colour to be a balance between modesty to fit within the urban context consisting of Gründerzeit dwellings from the 19th century and vivid enough to brighten up the wooden facade which would be subject to turning grey over time due to exposure. The pattern makes it possible to pass-through the light. In the RDU, a 45% colour coverage was chosen for the facade and a 25% coverage for the roof edge, which therefore looked as a slightly darker shade in comparison with the facade. This difference in coverage allows for optimalization of the energy generation of the PV panels where the overall architectural design supports it. Conventionally, a hexagonal pattern is used. However, the patterns are printed by 3D printer and the only constraint for the pattern shape it that it is a tessellating shape, and therefore infinitely repeatable in order to blend uniformly together when viewed from a distance. In the RDU, the shape of the building itself, was therefore used as the tessellation pattern printed on the PV panels as visible in figure 7 on the right.

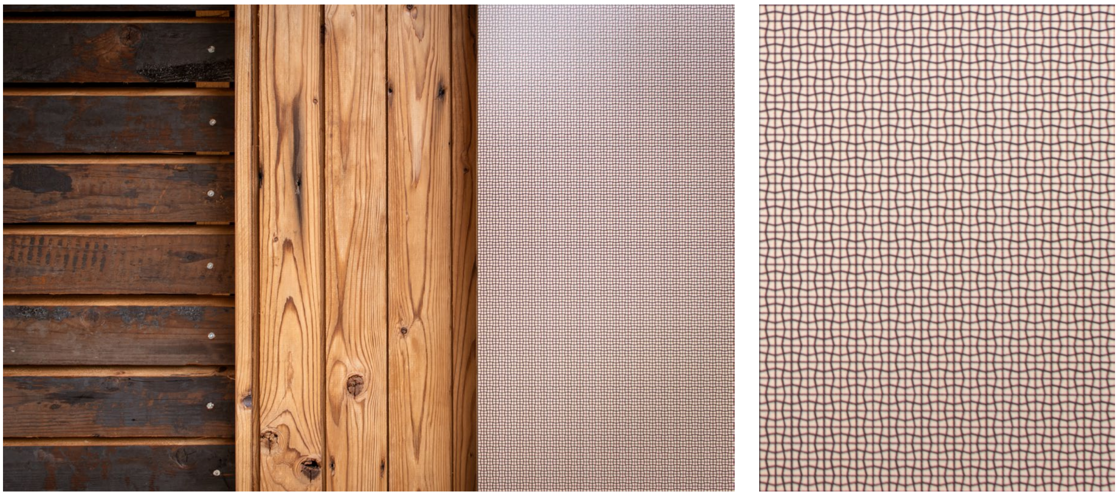

Fig. 7: (right) A detailed facade fragment where the solar panel meets the recycled timber cladding. (left) A more detailed view of the solar panel, where the printed tessellation pattern can be seen that resembles the shape of the building.

Together, all of the customized parts of the facade panels of ripple creates a stronger integration of the BIPV/T system and make it an indispensable part of the overall building concept, which resonates in the materials used. The formal integration of BIPV/T elements makes spatial optimisation possible as it is possible to create the desired amount of BIPV/T panels in the cladding of each facade and use other building elements where BIPV/T elements are not desirable, such as in the north facade. As was demonstrated in the RDU, this would be different in each facade according to the orientation of the building and the climatic conditions in the specific scenario.

Endless customization can however create an vast increase of elements with different specifications in the project, which could potentially increase manufacturing time. This was prevented through standardization of the most time-intensive tasks in the manufacturing process, which is the implementation of solar cells. The customization of the glass panel shape was used in a restrained way that neutralizes impact on the production process, because each panel had a similar solar cell configuration. This makes it possible to construct a custom solar facade with various shapes within production capabilities.

Lastly, it was found that the implementation of the BIPV/T facade in the RDU allowed for the education of the public on the way that energy can be generated in the buildings shell in a way that enhances the architectural expression of the building. This is, however, only possible through a close collaboration between engineers, designers and manufacturers, as it requires multidisciplinary input.

3.2 Measurement results

The overall energy balance during the measurement period, as well as the data describing the self-consumption is shown in figures 8 to 11. In total, more energy was generated than consumed during the competition period, as shown in figure 8. Figure 9 shows the daily generation and consumption of AC electricity by the BIPV/T system. Figures 10 and 11 describe the self-consumption of the RDU. A self-consumption of 1 indicates that all the generated energy was used and no feed-in occurred. The average self-consumption index is 0.73.

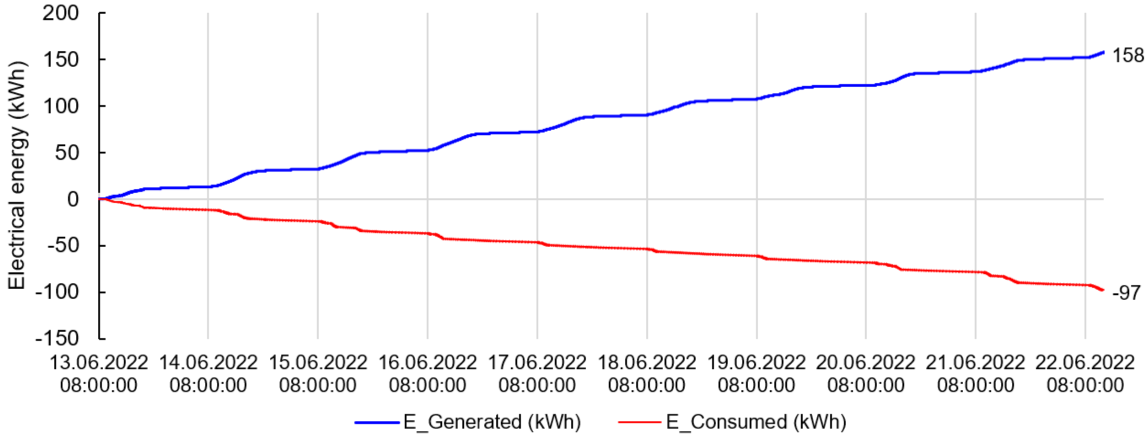

Fig. 8: Cumulative energy balance

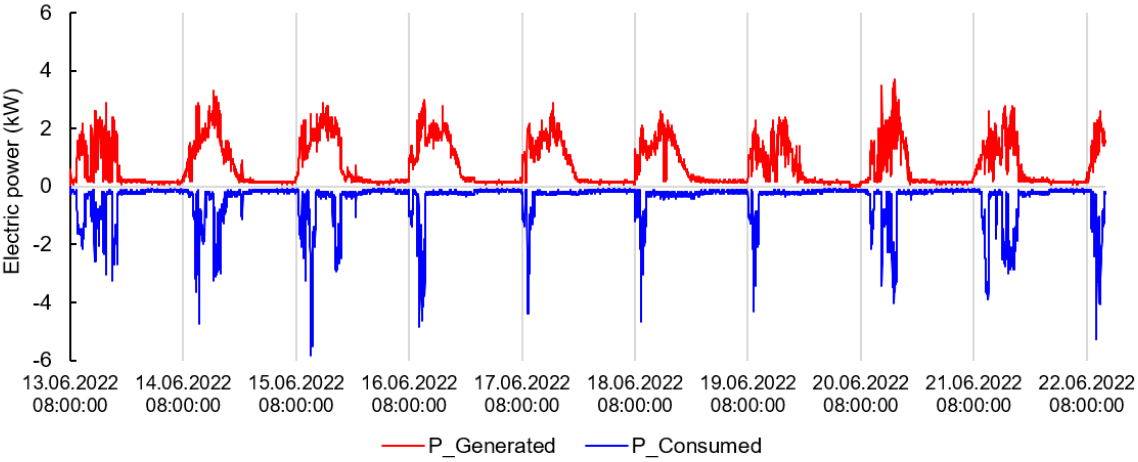

Fig.9: Total AC electricity generated and consumed on site

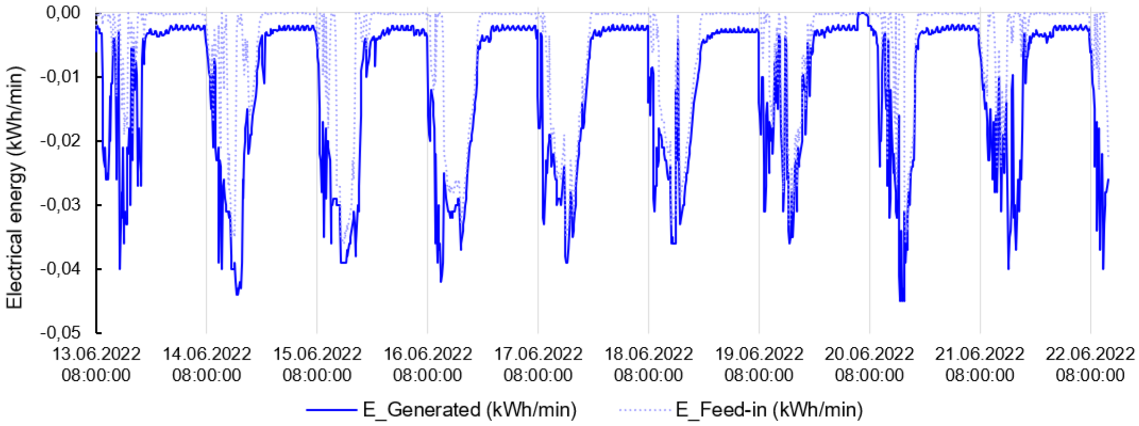

Fig. 10: The electrical energy generated on site or fed into the electricity grid, measured at a 10-minute interval.

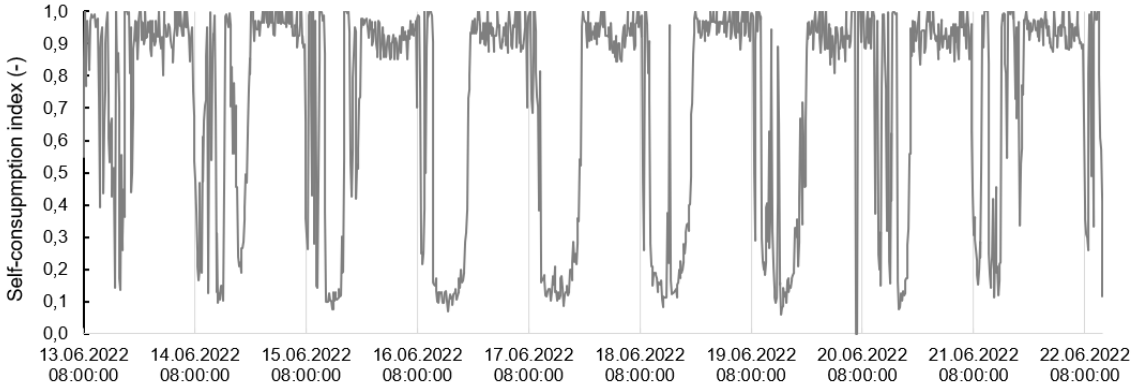

Fig. 11: Self-consumption index, calculated based on the measurements of generated and feed-in electricity

4. Conclusion and discussion

The use of the RDU as a physical prototype to conduct research has given novel insights in the possibilities on optimising, customising and aesthetically integrating solar design to make the use of solar power in buildings more efficient, a before rather neglected area of research (Attoye et al., 2018; Munari Probst & Roecker, 2007).

Firstly, the optimisation of the solar design was researched and evaluated through both a technological and architectural perspective. The optimal tilt of the PV modules along solar belt improves the energy generation potential of the BIPV facade. In addition, the building element can be replaced where it is not needed for other functions such as bird houses for increasing biodiversity. By the implementation of coloured BIPV modules on the East and West façades, a higher energy production is made possible during the morning and evening hours.

Higher-efficiency PV modules were used on the roof to ensure a higher yield from a small area, leaving space for other roof usage such as a green roof and roof terraces. The further optimalization of the solar facade was realized through placement of a higher number of solar panels on the south and west facades in comparison to the east and north facades, with higher-efficiency solar panels at the tilted parts of the solar belt. It additionally brings continuity to the architectural expression of the facade.

Furthermore, the performance of the BIPV/T system in combination with the energy management system was evaluated. During the period in which the energy generation and consumption was measured, it was found that more energy had been generated than consumed. Moreover, the system shows a relatively high self-consumption (average 73%). In comparison, a review of literature (Luthander et al., 2019) indicates that PV systems with a similarly small battery may have an average self-consumption of 60% and systems with demand side management have a self-consumption of 42%. In the RDU, both demand side management and a battery are used, which further helps to increase the self-consumption.

Secondly, the used solar panels allow for customisation and were therefore designed to be fitting to their facade composition and other facade elements. Additionally, the unique shapes of solar panels are standardised in such way that it makes the production process relatively straightforward, while still allowing for a high amount of customisation. This high level within customisation possibilities makes it possible for the solar system to be relatively easily adapted and applied to other buildings within different urban contexts, fitting the principle of universally specific and allowing for application on a large scale.

Lastly, it has been evaluated whether it is possible to integrate BIPV/T in an aesthetically integrated manner from a holistic perspective. By making the solar design an integrated part throughout the entirety of the building design process, it was possible to implement the design guidelines defined by Probst et al. (2007). Due to the close collaboration between students of architecture, engineering and the producer of the PV modules, it has been possible to integrate the solar design in an architectural manner while still having a sufficiently high efficiency due to orientation, placement and colour choice.

By combining the findings on the three different aspects of solar energy efficiency, it was possible to build further on the design guidelines of Probst et al. (2007). The proposed additions are less focused on the aesthetics of integrating BIPV/T and more on the design process to make this integration possible. The following five guidelines are proposed:

1) To make optimal use of the potential for BIPV/T, solar design should be incorporated within the design process from the beginning. As soon as it is conceptualised within the primary design framework, solar design can become an integral part for both the energy system design and architectural building concept. This can greatly benefit rather than limit the overall building concept, the technological performance and its appearance.
2) To foster this integration of solar design into the design process, a multidisciplinary integration between system designers, structural engineers and architects is highly advised. A reciprocal awareness of both aesthetic requirements and technological and production possibilities and limitations of solar systems requires a constant collaboration between producer and designer.
3) Even though novel PV(T) technologies afford many varying and exceptional uses of solar design, it is advised to think about solar integration in a more subtle manner. The aim of BIPV/T is not to create a unique artwork but to embed the renewable technology on a wider scale within its urban context in a delicate matter. This requires nuances in material textures, hues and compositions rather than an expressive exploration of opportunities. As a result, solar technology can visually almost disappear, leading to an enhanced feeling of integration within the urban fabric.
4) In terms of technical performance, integrating solar thermal and photovoltaic installations may be beneficial in residential buildings. In order to achieve a higher self-consumption, energy storage with demand side management could be used.
5) Since the inhabitants may have a significant influence on the energy use of a building, it may be beneficial to have a larger focus on user experience and increasing environmental awareness. Although dependent on the specific user, a physical interface may encourage the occupants to interact with the energy management system.

The findings of the conducted research show how a close collaboration between architect, engineer and solar design company can establish architectural integrability while being realistic about the technical limitations. Moreover, the advantages of improving not only the technological part of the energy system but also its visible appearance is demonstrated. It shows an alternative to the conventional roof PV panels perceived to be a limit in the design of buildings by residents, urban planners and architects. With this, the authors hope that the RDU provides an example of the integration of a solar system in architectural design, it being a start of the systematic implementation of BIPV/T in the design process of buildings. Perceiving BIPV/T as yet another architectural element – such as brick or wood – having its own limitations and opportunities rather than being an unavoidable element to contribute to sustainable housing would increase the immediate implementation of solar systems in buildings. The authors therefore agree with Yang & Athienitis (2016, p. 887): *"Establishing BIPV/T systems both as a standard architectural concept and as a functional building component replacing conventional claddings, roofing materials, would aid in the widespread use of BIPV/T systems"*. When applied on a large scale, this could contribute to the acceleration of the global energy system transition.

4.1 Improvements and limitations

This study has taken place in the context of the Solar Decathlon Europe which resulted in certain regulations and limitations to be complied with. Firstly, due to a limit to the capacity of the PV installation (3000 Wp), only the PV modules at the most efficient locations were connected instead of the whole BIPV/T facade and the full energy generation potential of the BIPV/T design could not be tested. Subsequently, the measurement results cannot be used to evaluate the influence of east and west oriented BIPV facades in increasing the energy generation during the morning and evening hours. Additionally, the entire building diverged from the south-west orientation, such that the west facade was slightly oriented towards the South. This likely influenced the energy generation in the evening hours. Finally, the performance of the solar thermal systems could not be evaluated independently since the type of measurements conducted during the contest are not suitable to assess the performance and efficiency of the systems.

The design of the RDU itself also demonstrated certain limitations: due to the combination of an accessible roof and the tilted solar belt, it was necessary to implement a transparent, glass balustrade to transfer sunlight towards the PV cells. This resulted in a considerable carbon footprint due to the excessive amount of glass and aluminium used. Furthermore, the current system of construction led to a significant increase in building time. This was mainly due to a discrepancy between the tessellated solar panels and the conventional substructure design, giving rise to difficulties in placement and levelling. The aesthetic evaluation of residents was neither considered in this study. In addition to these technical and aesthetical limitations, the affordability and viability of the BIPV/T was currently neglected in this study since the aim was to create a functioning prototype.

A consecutive design should consider these wide-ranging issues, and further research is recommended to test the feasibility of flattening the energy peak throughout the day to unite the demand and supply of solar energy. In addition, the BIPV/T implementation and different energy storage options could be studied on a wider scale, such as a neighbourhood. Moreover, to make solar design inherently part of the toolbox for urban architecture, policy changes should accommodate this development. In general, future studies could investigate the optimal balance between aesthetics, customisability and optimisation to develop the rate of adoption of solar design within urban contexts.

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