ELECTRICAL INTEGRATION OF PHOTOVOLTAICS INTO BUILDINGS

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ABSTRACT: This work outlines how advances in the electrical system of buildings can aid in the integration of photovoltaics (PV) and a holistic system optimization. In a time of urgently needed defossilization of new or deeply renovated buildings, they are essential to achieving (Near-)Zero Energy Buildings (ZEB). Key points are a better integration into the planning process, prefabricated elements, smart power converters, plug & play interconnection solutions and advanced, self-learning energy management systems (EMS), with direct-current (DC) networks as a forthcoming alternative to the alternating-current (AC) standard. In addition to a high degree of self-sufficiency, they also support the handling of grid constraints and advanced grid requirements, while enabling financial optimization of the design and operational aspects. Several technological developments are required to enable the implementation, and we are outlining novel approaches for key elements.
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1 INTRODUCTION

The global building-integrated photovoltaics (BIPV) market has reached a volume of EUR 20 bn and is expected to grow substantially, reaching a CAGR of 21.2% over the next five years [1]. In Europe, which currently has a market share of 37%, the growth is expected to exceed the global average. Here, the increase in installations will be fostered by the Energy Payback Directive for Buildings with its latest recast published in 2024 [2], requiring new buildings to reach zero-emission status latest in 2030. It is further complemented by the Renovation Wave Strategy [3] as well as national and regional plans.

Next to the generation of electrical energy in buildings or their surroundings, effective power conversion, energy management and electricity storage are required to ensure effective use of the generated energy and ensuring maximal self-sufficiency. This will require advanced solutions for each of these sectors. We consider that this aspect of building integration is as of yet undervalued and should receive more attention of the research and industrial communities.

At the same time, BIPV implementation is still hampered by the fact that it is not fully integrated into the value chain of buildings. A lot of individual planning is needed for every project, bespoke design is the rule, and the integration is a complex, multi-party venture. This is effective when producing highly individual, often very attractive, building solutions, but is not conducive to a wide roll-out of the technology to serve the purpose of defossilization at scale. Conversely, building-*applied* PV has established its own sales channels, largely by being sold as an add-on instead of integrally.

Buildings of the future will have to be energy-active units, and every owner of a building – new or renovated – will have to consider in the next few years how to deal with electrical energy in an effective manner, and to implement an electrical system that serves this purpose. This also creates opportunities for enhanced self-sufficiency, backup functionality, and trading grid services providing extra revenues. In a joint exercise of the partners of EnergyVille – KU Leuven, VITO, imec and UHasselt, we want to address the underlying issues and provide novel solutions that foster the uptake of PV in and on buildings. We are therefore also looking for partnerships to address the various aspects of this task.

2 TECHNICAL BACKGROUND

The subject field is grouped into four topical areas. The following subchapters outline briefly the state of the art, and room for improvement which we identified and aim to address.

2.1 PV in Building Elements

In order to reduce the amount of work, especially on the construction site, efforts are made by the building industry to prefabricate elements as much as possible. A typical example are curtain wall elements containing insulation and glazing, being installed at e.g. office buildings by attaching them to the floors of the structure. But also in renovation, prefabrication is increasingly used, such that the on-site work can be executed quickly, and methods have been developed to tailor these elements to the specifics of the respective building, as depicted in Figure 1. In order to integrate PV, and preferably also converters, into these structures, novel techniques are still to be developed; see the following paragraph.

2.2 Power Converters

The installation situation of PV in buildings is characterized by high variability in sizing and irradiance, especially owing to shading. Microinverters are used in some cases to provide sufficient flexibility, while string inverters are the most prevalent solution, often complemented by power optimizers for better adaptation to variations in irradiance. For either solution, integrating them into façade or roof elements is critical, with uncertain reliability under the challenging thermal conditions. While control is normally executed through a Modbus connection, data extraction uses the same or the manufacturer's cloud space.

2.3 Electrical System

BIPV systems are generally connected similar to building-attached installations, requiring wiring at the time of installation, with additional complications due to the need to integrate into the building elements and the fact that the thermal insulation and moisture barrier function need to be maintained. The main electrical system of a building is realized in alternating current owing to standards and the large availability of components as well as the fact that the main supply is provided by the AC electrical grid. Meanwhile, a lot of

appliances use DC systems internally, such as lighting, desktop equipment, and nearly all equipment employing variable-speed electrical motors, often including HVAC components and heat pumps. For the latter, the availability of DC-supplied devices is currently still limited. Obviously, novel systems such as PV, batteries and increasingly electric vehicle (EV) charging, run on DC, opening the consideration whether novel systems should be designed according to emerging standards for this technology.

Figure 1: Schematic visualization of building renovation with prefabricated elements. Image courtesy of BuildUp Offsite

2.4 Energy Management

While conventional grid-supplied buildings only offer limited flexibility and thus do not require energy management aside of load limiting, this need clearly arises with the implementation of PV generation and additional appliances that offer the opportunity of load scheduling, e.g. with heat pumps and vehicle charging. This is complemented by the fact that efficient management can enhance self-sufficiency and self-consumption of the generated energy as a means of economic optimization. Further to that, on the grid side time-variable pricing and the opportunity to offer flexibility of load and/or grid injection are becoming key points of optimization. Increasingly, limitations in the load capacity of the grid, especially in local feeders, lead to time-dependent constraints of either injection or withdrawal that need to be taken into account in the scheduling. A variety of EMS's is available today, covering the main functionality described here, and increasingly implementing machine learning of generation and consumption patterns in addition to grid pricing and weather forecasts.

3   NOVEL CONCEPTS

We are proposing a set of novel technologies that can help foster the integration of (BI)PV into buildings and the optimal use of the generated electrical energy. They generally consist of parts that have reached medium Technology Readiness Levels (TRL) already and can be demonstrated as prototypes, parts that are working in the laboratory and others that require initial testing before deciding about their further development.

3.1 Integration of PV into Building Elements

On the side of the PV modules themselves, novel cell interconnection technologies are being developed that allow flexible form factors and remove the need for busbars connecting adjacent strings. This helps to streamline the manufacturing process and can be done with multi-wire techniques and in-laminate soldering, while embedded reverse diodes can reduce the risk of overheating cells due to shading. For the integration of the PV element into the building element, advanced planning methods need to be established. They should comply to Building Information Modeling (BIM) standards to simplify the design and manufacturing processes. Part of the process also needs to be the modeling of energy yield such that reliable predictions become possible.
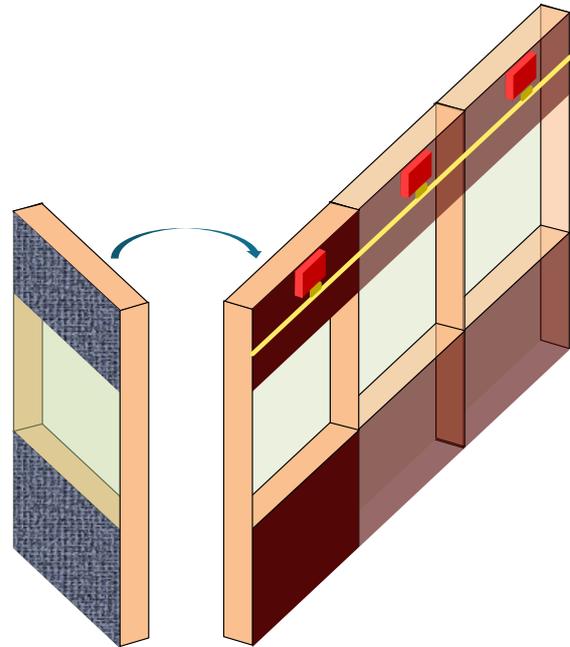

Figure 2: Curtain wall element with integrated PV, power converters and bus interconnection

3.2 Smart Power Converters

In order to simplify the integration into NZEB, we are aiming to develop a new class of power converters that can adapt smartly to the irradiance situation and ensure optimal extraction of energy from the PV panel without detailed planning. They need to feature self-monitoring to ensure continuous performance and, if required, preventive maintenance, and they should communicate the runtime status of energy production towards a management system in order to enable machine learning for performance prediction. Ideally, they should be integrated into prefabricated elements as depicted in Figure 2, whereby thermal stress and reliability aspects require particular attention.

3.3 Building Nanogrid

While AC systems form the backbone of a building's electrical grid for some time to come, DC systems can form a better solution eventually owing to less complex converters, less conversion losses, and, ultimately, lower overall system costs. Their introduction may start with the PV converters described above, whereby we aim to interconnect them with a power collection bus in a "plug & play" system, reducing the need for on-side wiring work. It can then be extended to hybrid systems with batteries, adding vehicle chargers, and, as they become available, DC-powered appliances, see Figure 3. The building-internal electrical system is thus independent of the grid constraints, and advanced requirements for inverters, as imposed e.g. by the new Requirements for Generators 2.0 [4], only need to be implemented in a single, albeit more complex, unit per building.
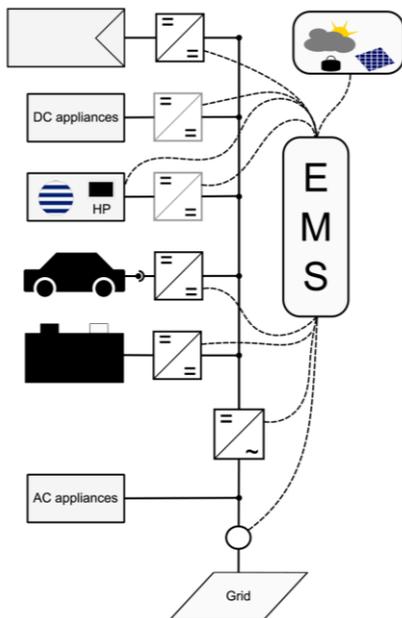
Figure 3: Schematic of a building DC nanogrid controlled by an Energy Management System

3.4 Advanced Energy Management

For the improvement of energy management systems compared to the state of the art, there are various options. A key element is machine learning, letting the system adapt to the energetic situation, and forecast energy-related parameters, regarding energy generation, consumption, also accounting for usage patterns, grid pricing, flexibility trading options and grid connection constraints. Advanced forecasting solutions contribute to this, relating geo-information with weather forecasts and taking into account physical information about the PV system, improving the parameterization with learnings from the operational phase. Adaptive thermal grey-box models of the building allow for improved leverage of heat pumps as flexible loads in combination with thermal inertia, while parameters of the devices can be steered in a more detailed approach than the current "smart-grid ready" techniques. Similarly, a learning system can leverage electrical storage and vehicle charging, and soon also vehicle-to-grid power transfer, for enhanced flexibility.

4 CONCLUSIONS & OUTLOOK

In this work, we described how advanced solutions for the electrical integration and energy management can improve the utilization of PV in and on buildings. They contribute to the valorization of the generated electrical energy. We envision that in the next few years, building owners will increasingly see the value and opportunities of PV generation in combination with storage, while the usage of heat pumps and electric vehicles will create an additional need. Effective management of the electrical system in combination with thermal aspects is becoming a must, aiding them in effectively utilizing the energy and minimizing their costs respectively obtaining additional earnings on dynamic energy markets while dealing with grid constraints and advanced requirements.

Improvements in several aspects of the electrical system can aid a full integration of BIPV into the value chain of the building industry, opening the space for collaborations between research institutions and companies. Smart integrated converters, the combination with prefabricated building elements, advanced energy management and eventually DC microgrids will provide solutions that facilitate the implementation, but need further R&D and testing before being ready for the market. Current research programs provide only moderate support for these integrative tasks.

5 REFERENCES

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7 LOGO SPACE