Embedded BIPV Module-level DC/DC Converters: Classification of Optimal Ratings

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Abstract

Building-integrated photovoltaics (BIPV) is seen as a key technology to reduce the environmental impact and net power consumption of buildings. The integration of PV into building components, such as façade, window, roof or shading elements, leads to a distributed generation over the building envelope with a profound impact on the electrical installation. Designing the electrical system with string inverters and a possible wide variety of module sizes and technologies is a challenging task. To overcome this issue, Module-Level Converters (MLCs) can be used. A supplementary benefit is that the consequences of partial shading can strongly be reduced. This paper investigates whether the current generation of MLCs is suited for embedment in facade BIPV modules. The PV output is categorized and compared to the input parameters of the converters. Besides the discrepancy between the physical dimensions of the converters and the desired installation location, thermal and electrical measurements on a prototype BIPV curtain wall element reveal that daily energy losses can be as high as 50% due to thermal overload when used in a moderate climate such as Belgium. The paper concludes by discussing further standardization of BIPV module-level converters.

Keywords: BIPV, DC/DC converters, module-level converters, LVDC, curtain wall

1. Introduction

The use of Building-Integrated Photovoltaics (BIPV) is facilitated by decreasing costs of PV materials, enabling structural integration in the building envelope. A large variety of BIPV elements are already available on the commercial market such as windows, roof tiles or façades [1, 2, 3].

European legislation endeavors to further increase BIPV penetration via several directives such as the Strategic Energy Technology (SET) Plan and the Energy Performance of Buildings Directive (EPBD), requiring that all public buildings are near Zero Energy Buildings (NZEB) from 2020 on [4, 5]. The integration of BIPV into building façades is seen as a key solution to achieve this goal in an urban context where the available roof area is scarce compared to the abundance of available vertical surfaces [1, 6].

Given the commercial profitability of companies in the sector and several pilot projects around the world, BIPV can be seen as a promising technology. There is however still a strong research interest to further drive down costs and to improve the technical aspects of BIPV modules and BIPV installations. Technological advancements show that both the efficiency and appearance of BIPV solar cells continuously improve over the years for transparent [7] and non-transparent applications [8, 9]. Also the impact of BIPV on the thermal performance of the building is recently gaining more interest [10, 11, 12].

Façade BIPV systems are currently evolving in two directions. To date, most buildings with BIPV are entirely custom-designed and the appearance and prestige of the project are considered more important than the energy yield and payback time. Next to the currently existing market, the need for standard off-the-shelf BIPV modules has been identified [3, 13, 14]. Off-the-shelf modules are expected to represent a future mass market for façade BIPV. Several practical obstacles however still obstruct large-scale penetration of these standardized BIPV modules such as the integration of the electronics and their reliability [15], and an easy practical method to electrically interconnect the BIPV modules from one to another.

This work will focus on BIPV curtain wall elements with integrated (embedded) DC/DC Module-Level Converters (MLCs). By integrating the converter in the frame of the BIPV module, local Maximum Power Point Tracking (MPPT) can be achieved. This approach leads to lower engineering effort to design the electrical system, lower installation costs during construction and a higher overall system efficiency. This concept and the advantages thereof will be explained in further detail in section 2. Part of the curtain wall element is glazing whereas the other part is the PV module. Since several types of PV technology can be used in this curtain wall element, section 4 will investigate the two most commonly used BIPV materials for a case study building. Focus is put on the differences in output voltage, current and power and a classification is proposed. This serves as an input for section 5 where commercially available MLCs are compared and their suitability for integration is evaluated. In section 6, the need for dedicated BIPV MLCs is further formalized by a proposed standardization of the MLCs and a discussion the preferred PV technology. Section 7 concludes this paper.

2. Modular BIPV systems

2.1. Concept

The concept of modularity in BIPV curtain walls was already introduced by Goncalves et al. [11] but further focus on the electrical aspects of this concept is presented here. To facilitate façade installation, pre-fabricated curtain wall elements are extensively used in the construction sector. The outer frame is typically an extruded aluminum frame whereas the outer surface can be made of a large variety of materials such as glass, plastic or metal. Due to its simplicity, installation costs can be reduced and the architectural freedom to design an appealing façade is only minorly restricted. The latter is an important aspect to consider as low creative freedom could hold back architects from using BIPV technology [16].

Typically, curtain wall modules are divided into a transparent and a non-transparent part, as shown in Fig. 1. The non-transparent part is usually located between two adjacent floors to hide the technical equipment which is above the false ceiling. For optimal PV efficiency, the focus in this work is on replacing the non-transparent passive part by an energy-producing (active) element. Placing PV modules in curtain walls is already undertaken by several companies in the BIPV industry [2, 3]. Current projects however remain an entire custom design which is a consequence of and maintained by a lack of standardization in the sector. Not only the curtain wall dimensions vary over different projects but also the design of the electrical installation is challenging as string inverters are used.

The large majority of BIPV literature still reports using string inverters [17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28]. An exception to this is the Copenhagen International School in Denmark where micro-inverters are used [29]. To use a string inverter, panels with similar I-V characteristics and shading profiles need to be selected by the electrical design engineer and cabling needs to be done on site by a skilled construction worker. Both aspects increase the amount of manhours in a project, which adds to the costs of the installation. Next to the capital investment itself, the energy production and thus revenues can be lower in contexts where partial shading occurs because shaded cells limit the performance of the entire string. Energy losses in the order of 5-35% are reported as a consequence of partial shading in BIPV systems [30, 31, 32, 28].

To overcome the problems due to partial shading, module-level MPPT is preferred over string-level MPPT. This can be done by MLCs which should then be integrated in the aluminum framework of the BIPV module. Another major advantage of this approach is that the electrical network layout and thus the cabling can be further simplified if all modules are connected in parallel to the same bus. This electrical topology is shown in Fig. 2 and was first introduced in [33]. Note that a Low-Voltage DC (LVDC) architecture is assumed instead of the more conventional AC system. In applications such as datacenters, LVDC systems are already employed as they offer specific advantages such as a higher

Figure 1: Front view and vertical cross-section of the prototype BIPV curtain wall element with indication of the used materials.

overall efficiency, lower costs and a higher reliability due to fewer components. For office buildings in general, the use of LVDC is preferable regarding the high penetration of DC consumers and because higher system efficiencies can be obtained by reducing the amount of conversion steps.

From an economical point of view, the main drawback of using MLCs is the higher price per installed Wp compared to string inverters. However, it is expected that this disadvantage will be overcome in the near future as converter prices will decrease due to mass production [33]. Next to this, integration of the MLC in the frame leads to a strong reduction in man-hours. When converter integration and wiring is part of the pre-fabrication process, the mechanical and electrical installation can occur simultaneously and be done by a construction worker. An electrician is only required to connect the BIPV feeder to the main LVDC bus.

From an engineering point of view, frame-integration poses however several practical difficulties that need to be overcome. Placement in the hollow cavities of the aluminum frame is preferred over more conventional attachment to the rear side of the PV panel because insulation materials are placed behind the

Figure 2: A schematic overview of the electrical installation of curtain wall BIPV modules connected to a LVDC grid - All elements have a dedicated MLC, of which the outputs are connected in parallel to the same DC bus that runs from one module to another. The bus voltage is stabilized by a central DC/DC voltage balancer.

PV panel in façade applications. A specific form factor is thus required: an
120 elongate rather than a square design. The thermal design is also a concern
due to the limited cooling possibilities and the high ambient temperatures that
occur near the PV panel. This could lead to eventual reliability problems due
to the high steady state temperature and the large temperature swings. Further
issues related to the power electronics converters will be discussed in section 5.

125 Another positive consequence of using exclusively MLCs in the BIPV mod-
ules are potential reductions in the fabrication costs of the PV panel. PV
modules now need to comply with standards and test procedures which stem
from conditions that occur in string operation such as IEC61215 and IEC61730.
Series connection of the panels leads to a higher system output voltage. Decent
130 electrical insulation is critical as for example flash-over can occur between a pole
(+ or -) of the PV panel which is at a high potential and the metallic frame,
which is earthed and thus on ground potential. To prevent this from happen-
ing, sufficient distance needs to be respected between the frame and internally
electrical conducting components such as the cells and conduction strips. Com-
135 mercial PV panels are tested for systems up to 1000 or even 1500 V breakdown
voltage. If the BIPV modules are restricted to work with MLCs, test standards
can be relaxed since the max voltage between the frame and the PV output
terminals is restricted to the voltage of the panel itself. As a consequence, the
energy density of the module can be increased as the cells can be placed with
140 less clearance with respect to the edges of the module. For the same output
power, this leads to a lower cost per watt peak of the modules due to savings in
materials (smaller total surface) and packing/transport. The use of a lower DC
voltage also reduces the risk on arc-faults that could lead to fire.

3. Methodology

145 An example layout of a curtain wall module is shown in Fig. 1. A prototype
measuring 270 cm by 109 cm was built and installed in the façade of a test
building to measure the electrical output and to verify and validate BIPV mod-

els. This prototype BIPV module is based on an actual curtain wall element of a building in Brussels, Belgium. The mechanical properties of this curtain wall module serve as an example in the remainder of the manuscript. The actual
150 prototype has a fixed area dedicated for PV cells. In this manuscript we investigate the impact of changing this PV-decicated area from 0 to 100%, as can be the case in actual designs. Furthermore, the electrical properties of different PV technologies (c-Si, c-Si half cells and CIGS thin film) are evaluated.

155 The obtained results are then compared to the voltage, current and power range of commercially available MLCs. As explained in Section 2, DC/DC converters connected to a LVDC grid are envisioned for the modular BIPV approach. To the best of our knowledge, there is however only one manufacturer that designs Parallel Power Optimizers (PPOs) and it was therefore decided
160 to include Micro-Inverters (MIs) and Series Power Optimizers (SPOs) in the comparison to broaden the overview.

Not only the electrical requirements for BIPV curtain wall modules are investigated. Also the possibility to integrate them in the framework of the BIPV module is checked by comparing the dimensions of the MLC to the available
165 space in the aluminum tubes of the curtain wall element. Besides the dimensional requirements, this environment is harsher from a thermal point-of-view. Thermal measurements that were obtained from our test setup indicate temperatures that exceed the maximum operation limit of the converters. The resulting daily energy loss due to converter autoshtutdown is calculated by combining the
170 thermal measurements with the electrical measurements of our test site.

More details on the module itself, the measurement setup and experimental results regarding the electrical and thermal performance can be found in [10, 11, 12].

4. Output range of modular BIPV

175 To evaluate the performance and rating of MLCs, this section provides an overview of the expected output range of modular BIPV systems. The output

voltage, current and power of the BIPV module needs to correspond with the input rating of the MLC. Compared to mainstream c-Si 60- or 72-cell PV panels, a much larger variety of output ratings will be observed for modular BIPV systems due to the difference in size and thus in the amount of cells. Even more complexity is added by shingled half and quarter 6" cells, 5" cells, as well as by CIGS and CdTe thin films that have very different per-cell V_{oc} . This section will quantify this difference and serve as input for Section 5.

4.1. Materials and results of specific test setups

Practical experience with BIPV elements was built up over two projects, namely the EFRO funded SolsThore and INTERREG funded PVOpMaat project. The obtained results will be discussed in this section.

The two main BIPV technologies are c-Si and thin film (TF). Six inch industrial c-Si cells can have rated short-circuit currents (at STC) in the order of 10 A for bifacial technologies, while the rated open-circuit voltages can vary widely, depending on the number of series connected cells in the BIPV module.

In the prototype curtain wall BIPV element of Fig. 1, a typical 60-cell module with monocrystalline PESC cells was used with rated V_{oc} of 38 V and I_{sc} of 8.5 A [11]. In some designs it would however be more practical to have the same area as a transparent window in the upper part of the curtain wall element, and the PV module in the square area below, reducing the cell count to 36 and the rated V_{oc} to about 23 V. Furthermore, the lower part, which is now a triple glazing window, could also be a semi-transparent thin-film PV module of 164 cm by 109 cm, with its own, dedicated MLC. As the TF cells are quite narrow, high rated V_{oc} can build up quickly over rather short module widths. Moreover, CdTe cells have a typical V_{oc} above 0.8 V.

In the same test building as in [11], experimental semi-transparent CdTe BIPV windows of 60 cm by 120 cm and rated V_{oc} of nearly 120 V are being monitored. SolarEdge P405 series power optimizers with 125 V input voltage limit were used in this setup but additional overvoltage protection circuits were needed to avoid MLC breakdown during winter, when the BIPV demonstrators

are expected to exceed the 125 V limit. The rated I_{sc} of those BIPV demos is quite low, in the order of 0.5 A at STC, while the rated power is about 60 Wp, mainly due to the high series resistance. With TF BIPV, there is a wide range of possible currents and voltages for a given fixed area, depending on the internal cell interconnection schemes (paralleling and serializing). For the above relatively small area, the same CdTe PV maker also offers more powerful versions for each transparency level (up to 20 Wp higher), with rated V_{oc} in the order of 67 V and I_{sc} slightly above 1 A.

Mainstream or novel c-Si PV based on six inch cells are however not the only candidate for BIPV applications. Module designs with half cells, some with shingle configurations (overlapping cell edges for higher power densities while reducing the resistive losses) can result in rated I_{sc} in the order of 4-5 A and V_{oc} in the order of 70-100 V. Also, modules with 5 back-contact (IBC or IBC-HIT) cells can be very suitable for façade BIPV systems, as they offer high efficiency and often cell-level bypass diodes for better partial shading mitigation. These technologies feature high per-cell rated V_{oc} (720 to 760 mV), meaning about 70-75 V for a normal-sized 96-cell module. This value is still far from extreme. The typical rated I_{sc} values are in the order of 7 A.

4.2. Case study

Consider the façade shown in Fig. 3 which serves as a case study to further investigate the electrical output parameters that may occur in curtain wall BIPV systems. The façade is built using BIPV curtain wall elements and the area taken by PV can differ from one module to another. The surface dedicated to PV, S_{PV} , increases stepwise by 10% compared to the total surface S_{tot} of each module. The dimensions of the curtain wall are similar to the prototype which was developed and discussed in Section 2.

Three cases with different PV technology are considered: regular c-Si, half-cell c-Si and CIGS thin film. Each of these cells has different dimensions and electrical parameters. The half cells are considered to be derived from the regular sized c-Si cells, assuming that the total surface (per two cells) remains

Figure 3: Appearance of one floor level of a case study building with BIPV curtain walls

the same whereas the voltage doubles and the current halves. To achieve a high output voltage, the cells are always assumed to be series connected. An overview is given in Table 1.

240 A large spectrum of voltages and powers is covered over the different technologies and module dimensions. The output voltage ranges from 3 V up to 216 V whereas the power rating starts at 26 W and goes up to 452 W. All cells are series connected and consequently I_{MPP} remains the same per technology over the different module sizes. It changes over a more limited range from 1.54 A
 245 up to 8.3 A in the MPP. Note that high-efficiency monofacial and bifacial c-Si cells can output about 20-25% higher currents.

In the next section, the discrepancy between electrical output characteristics of BIPV as given in Table 1, will be compared to the input parameters of available MLCs as shown in Table 2.

Table 1: Electrical parameters at STC of the ten different BIPV modules in the case study façade. The modules are evaluated for c-Si, half cells c-Si and CIGS thin film technology of which the individual cells are series connected to achieve a max output voltage.

BIPV module	1	2	3	4	5	6	7	8	9	10
#										
S_{PV}/S_{tot} (%)	10	20	30	40	50	60	70	80	90	100
<i>Mono-crystalline c-Si cells</i>										
Cell dimensions: 157 mm by 157 mm										
Total # cells	6	18	30	36	48	60	72	78	90	102
V_{oc} (V)	3,80	11,41	19,02	22,82	30,43	38,04	45,65	49,45	57,06	64,67
I_{sc} (A)	8,86	8,86	8,86	8,86	8,86	8,86	8,86	8,86	8,86	8,86
V_{MPP} (V)	3,21	9,63	16,05	19,26	25,68	32,10	38,52	41,73	48,15	54,57
I_{MPP} (A)	8,30	8,30	8,30	8,30	8,30	8,30	8,30	8,30	8,30	8,30
P_{MPP} (W)	26,64	79,92	133,20	159,84	213,12	266,40	319,68	346,32	399,60	452,88
<i>CIGS thin film cells</i>										
Cell dimensions: 1090 mm by 6 mm										
Total # cells	45	90	135	180	225	270	315	360	405	450
V_{oc} (V)	27,00	54,00	81,00	108,00	135,00	162,00	189,00	216,00	243,00	270,00
I_{sc} (A)	1,74	1,74	1,74	1,74	1,74	1,74	1,74	1,74	1,74	1,74
V_{MPP} (V)	21,60	43,20	64,80	86,40	108,00	129,60	151,20	172,80	194,40	216,00
I_{MPP} (A)	1,54	1,54	1,54	1,54	1,54	1,54	1,54	1,54	1,54	1,54
P_{MPP} (W)	33,11	66,22	99,33	132,44	165,54	198,65	231,76	264,87	297,98	331,09

Figure 4: Graphical representation of I_{MPP} and P_{MPP} as a function of V_{MPP} for the case study on the BIPV curtain wall module.

250 5. Commercially available power electronics converters

In this section, an overview of currently available commercial MLCs is given. Table 2 contains the relevant parameters to evaluate the integration of these converters in the BIPV module frame. Electrical parameters such as the nominal power, the MPPT voltage range and the efficiency are important to check the suitability with the expected voltage and current ranges that were discussed in
255 Section 4. Table 3 provides more details on the cavity dimensions for converter embedment such that the converter dimensions can be compared to the available space.

To give a broad overview of the current state-of-the-art, Table 2 contains
260 three types of MLC architectures: DC/AC micro-inverters (MIs), DC/DC Series Power Optimizers (SPOs) and DC/DC Parallel Power Optimizers (PPOs). The modular BIPV approach that was discussed in Section 2, is based on the

utilization of the latter (PPO). However, using this larger dataset enables to draw more general conclusions on the integration possibilities for BIPV.

Table 2: An overview of commercially available module-level converters

Brand	Model	$P_{out,nom}$ (W)	V_{MPPT} (V)	η (%)	Temperature range (°C)	Dimensions (mm ³)	Transformer isolation?	Power density (W/l)	ΔV_{MPPT} (V)
<i>Micro inverters (DC/AC)</i>									
Enphase	M250-60	250	16 -> 48	95,7	-40 -> +65	179x217x28	Yes	230	32
Enphase	M250-72	250	16 -> 60	95,7	-40 -> +65	179x217x28	Yes	230	44
Enphase	M215-60	215	16 -> 48	95,7	-40 -> +65	179x217x28	Yes	198	32
Enphase	IQ7	240	16 -> 48	96,5	-40 -> +65	212x175x30	Yes	216	32
Enphase	IQ7+	290	16 -> 60	96,5	-40 -> +65	212x175x30	Yes	261	44
Enphase	S230	220	27 -> 37	95,8	-40 -> +65	172x175x35	Yes	209	10
Enphase	S270	260	27 -> 48	95,6	-40 -> +65	172x175x35	Yes	247	21
ABB	MICRO-0.25	250	12 -> 60	96	-40 -> +75	266x246x35	Yes	109	38
ABB	MICRO-0.3	300	12 -> 60	96	-40 -> +75	266x246x35	Yes	131	48
ABB	MICRO-0.3HV	300	19 -> 75	96	-40 -> +75	266x246x35	Yes	131	56
SMA	SunnyBoy 240	230	23 -> 45	95,3	-40 -> +65	188x218x44	Yes	128	22
<i>Series Power Optimizers (DC/DC)</i>									
SolarEdge	P300	300	8 -> 48	98,8	-40 -> +85	139x165x41	No	319	40
SolarEdge	P370	370	8 -> 60	98,8	-40 -> +85	139x165x41	No	393	52
SolarEdge	P500	500	8 -> 80	98,8	-40 -> +85	139x165x49	No	445	72
SolarEdge	P404	405	12,5 -> 80	98,8	-40 -> +85	139x165x56	No	315	67,5
SolarEdge	P405	405	12,5 -> 105	98,8	-40 -> +85	128x152x50	No	416	92,5
SolarEdge	P505	505	12,5 -> 83	98,8	-40 -> +85	128x152x59	No	440	70,5
Huawei	SUN2000P	375	10 -> 80	99	-40 -> +85	125x85x25,5	No	1352	70
<i>Parallel Power Optimizers (DC/DC)</i>									
Femtogrid	PO300	250	8 -> 42	95,7	-40 -> +65	288x342x51	NK	50	34
Femtogrid	PO310	310	8 -> 42	97	-40 -> +65	135x225x50	NK	204	34
Femtogrid	PO330	310	12 -> 65	96,4	-40 -> +65	135x225x50	NK	204	53

*NK: Not Known

Table 3: Possible placement locations in the BIPV module frame and their dimensions

Location	Width (mm)	Height (mm)
1 - Top, bottom and lateral profiles	80	29
2 - Middle profile	150	75

265 5.1. Dimensions

At first, the outer dimensions of the converters are compared to the available space in the aluminum tubes of the BIPV module frame. Aluminum profiles with two different dimensions are being used, as shown in Fig. 6 and indicated in Table 3.

270 Analyzing the dimensions of commercial MLCs reveals that none of the listed converters suits the size requirements imposed by the BIPV module on location one. There is however a strong size difference notable between MIs and PPOs on one hand and SPOs on the other hand. The power density of SPOs is a factor of 1,5 up to 2 higher. Two outliers are the Huawei SUN2000P with a
275 power density over 1300 and the Femtogrid PO300. The low power density of the PO300 is because the datasheet only provides the dimensions with the installation bracket that surrounds the converter, leading to a size increase in both the length and width of the converter.

The trend of a higher power density for SPOs can be explained by several
280 reasons, which mostly relate to the circuit topology of the converter. At first there is a difference in output. MIs produce an AC output voltage whereas SPOs/PPOs output DC. MIs utilize typically two conversion stages: DC/DC and DC/AC. This approach requires more components compared to PPOs where only a DC/DC conversion is performed. The notable size difference between
285 PPOs and SPOs is due to the magnitude of the produced output voltage. For PPOs, the output is already directly compatible with the LVDC grid, of which the voltage ranges in the order of 350-400 V. The maximum output of the majority of SPOs is limited to 40 V, which is only around one tenth compared

to the PPO output voltage. Only by combining them in series and adding an
290 extra converter to control the output voltage allows to use them correctly.

Since the input (V_{MPPT}) and output voltage of the SPOs are not far apart
(e.g. a ratio of 0.15 to 1.24 for the SolarEdge P405), simpler power circuit
topologies with fewer components can be used. For example, SolarEdge reports
to use a buck-boost converter [34], which is one of the basic power conversion
295 topologies having a minimal component count (5). In contrast, Enphase reports
to use an interleaved flyback structure [35] which is required to boost the voltage
to higher levels. This topology employs twice as many components if the coupled
inductors are seen as two devices. The coupled inductors, sometimes referred to
as flyback transformers, are often bulky components. As a consequence, both
300 the efficiency and power density are lower compared to SPOs.

SPOs thus have the smallest dimensions of all considered options. Still,
placement in the BIPV frame is not possible for location 1, where the dimensions
exceed both the width and height requirement. For location 2, all SPOs fit in
the frame and also the Femtogrid PO310 and PO330 are valid options.

305 5.2. Efficiency

The weighted efficiency η is overall very high ($>95\%$) for all examined con-
verters. SPOs show efficiencies that reach nearly 99%. Their higher efficiency
can again be explained by the small difference in input-to-output voltage they
are designed for. As a consequence, high duty cycles resulting in higher switch
310 conduction losses can be avoided. It is expected that a clear distinction in effi-
ciency would be visible between the MIs and the PPOs since the latter avoid the
conversion from DC to AC. This difference is however rather small, in the order
of 0.4% between the PO330 and the ABB MIs. When comparing the former to
the Enphase IQ7, the difference is even negative, -0.1%. This small difference
315 can be due to a higher DC output voltage of the PPO compared to the internal
DC bus voltage of the MIs.

Figure 5: MPPT operating range of the investigated MIs, SPOs and PPOs indicated on a $V_{MPP} - P_{MPP}$ graph on which also the results of Table 1 are plotted. This figure indicates that a large portion of the BIPV modules is not covered by commercial MLCs. Mainly higher voltage TF panels do not match with the current commercial generation of MLCs.

5.3. MPPT range and nominal power

The MPPT range is an important parameter to compare converters as a wider range will increase the energy production, which decreases the payback time. When comparing the MPPT voltage range (V_{MPPT} and ΔV_{MPPT}) a large difference is again observed between MIs/PPOs and SPOs. The latter outperform with several models where ΔV_{MPPT} is larger than 70 V. A max V_{MPPT} of 105 V is observed, which is very suited for mainstream BAPV but this limit is too low for BIPV, especially if TF is used. A graphical overview of the power and voltage range for the three converter types is given in Fig. 5. The purple lines indicate the operating range of the converters and the blue, orange and yellow lines represent respectively c-Si, half cell c-Si and TF technology and are derived from Table 1. SPOs span the widest range covering nearly the entire spectrum of c-Si and half cell c-Si. The working area of MIs and PPOs is nearly equal and requires expansion towards higher powers and voltages.

5.4. Temperature range

All MLCs of Table 2 employ passive cooling techniques. Active cooling is beneficial to increase the power density and efficiency of the converter. When lower component temperatures can be achieved, the conduction losses also decrease, leading to a higher overall efficiency. The power density can thus also increase, as power density and efficiency are closely related [36]. However, passive cooling is the preferred option from a cost and reliability perspective [37]. Forced convection by using a fan is difficult from a reliability point-of-view as

the fan has a limited lifetime due to its rotating parts. Liquid cooling is consid-
340 ered to be too expensive but BIPV Thermal (BIPVT) could be an interesting
solution when not only the PV panel but also the electronics become part of
the cooling circuit. The MLC could then benefit from the cooling system that
is already available.

The majority of the investigated devices has an upper limit of 65°C at which
345 auto-shutdown occurs to prevent permanent failure. The ABB MICRO series
starts to derate above 65° C to completely turn off at 75° C. The SPOs have
the highest dropout temperature, being 85° C.

At our testsite where the BIPV prototype is installed, temperature and
power measurements were constantly made. This data was used to verify if
350 the temperature at the location where the converter will be placed, exceeds the
65° C limit. The temperature data from a thermocouple placed at the 'TOP'
location, as indicated in Fig. 6 was used. As can be seen from Fig. 8 there
were several instances during May, June and July 2018 when this limit was
crossed. These months have been selected since they represent the most critical
355 conditions in terms of temperature. Converter shutdown due to overtemperature
is a protection feature to increase the lifetime of the electronic components but
this leads to a certain energy loss. The converter used at the test site is a
Femtogrid PO330 PPO. Since this converter does not fit in the framework of
the module, it was installed in a climatized zone inside the test building where
360 no overtemperature occurs. However, to quantify the energy loss related to
high operating temperatures, the temperature measurements in the cavity were
combined with the output power measurements of the PV module. When the
threshold temperature of 65° C was passed, the output power was set to zero.
Fig. 8 show the daily energy loss due to overtemperature. This was calculated
365 using Eqn. 1 where $W_{lost,\%}$ is the daily energy loss in percent, W_{total} is the
total produced energy measured over one day and $W_{T>65}$ represents the energy

Figure 6: Angle view of the prototype BIPV curtain wall module with indication of the different possibilities for converter placement.

that is produced when the temperature is above the 65° C threshold.

$$W_{lost,\%} = \frac{W_{total} - W_{T>65}}{W_{total,dayn}} \cdot 100 \quad (1)$$

Figure 7 shows an example of the measured power and temperature profile over one day and indicates the temperature crossings and the associated energy loss (grey). Mainly during July, large losses would occur with a temperature limit of 65°C. Figure 8 indicates daily energy losses in the order of 20 to 50%. Belgium has a temperate maritime climate. If the same structure would be evaluated in more southern areas with mediteranean (e.g. Italy) or subtropical climate (e.g. United Arabian Emirates), even higher energy loss needs to be considered during summer. This results in a longer payback time of the installation.

Further information regarding the impact of temperature on the reliability of BIPV MLCs can be found in [38].

Figure 7: Measured temperature in the converter cavity and the anticipated energy loss due to overtemperature shutdown ($T > 65^{\circ}\text{C}$) shown on May 8, 2018.

Figure 8: Measured temperature in the converter cavity and the anticipated energy loss due to overtemperature ($T > 65^{\circ}\text{C}$) shown over a period of three months.

6. Discussion of the results

380 6.1. New product range for MLCs

As discussed in the case study of section 4, BIPV panels can produce a very wide variety of input voltages and currents. Today's generation of MLCs are optimised for mainstream 60-cell or 72-cell BAPV panels. In theory, they can be used at the low end of their MPPT and power range to serve the BIPV market. 385 This mismatch however means that they are not optimally designed for the low or the high end of the BIPV modules. Furthermore, current commercial models of converters do not have the required form factor to integrate them in the frame and thus make factory pre-installment more difficult or even impossible.

Given the large spectrum of output voltages and currents, it does not seem 390 cost-effective and efficient to employ a one-converter-fits-it-all approach for the modular BIPV system. Instead this paper proposes to split up the PV output voltage/current/power in different categories, as shown in Fig. 9. This categorization has several positive consequences that will further facilitate the electrical design of the BIPV modules.

395 By establishing distinct power and voltage ranges, converter manufacturers can specifically target the BIPV market with a portfolio of products that are consistent with the output of BIPV modules. From Fig. 9, it can be seen that one product segment per PV technology is suggested. This is a consequence of the large differences in V_{MPP} and I_{MPP} that were observed. Class 1, 2 and 3 400 correspond respectively with TF PV, c-Si half cells and regular c-Si PV cells. Furthermore, each class was subdivided three regions a, b and c. This was done to prevent extreme overdimensioning which would lead to very high costs when the same converter is used for very different power ratings. This could make the use of smaller BIPV panels uneconomical which is against the design philosophy 405 that is proposed. The proposed classification should not be considered dogmatic but rather as a guideline in determining new MLCs for the BIPV market.

The classification and standardisation of BIPV MLCs is also important in the context of the increasing digitalisation of Architecture, Engineering and

Figure 9: BIPV output characteristics classification in different zones based on voltage and current limits. Alternatively, power limits can be considered.

Construction (AEC) processes. Building information modelling (BIM) supports
 410 the AEC digitalisation by integrating the roles of all stakeholders in a project.
 Being part of the building envelope, BIPV systems have also been contemplated
 in the BIM development [39]. A BIM-based software tool called BIMsolar has
 been developed for the design and simulation of BIPV systems [40], in which
 the selection of inverters and MPP trackers appears as an integral part of the
 415 workflow.

6.2. Preferred PV technology

It was shown that the existing generation of MLCs that is available on the
 market does not match with the requirements of BIPV MLCs. An interesting
 question is which PV technology is most suited from a converter perspective to
 420 comply with the demands such as a high power density and a long converter
 lifetime.

The MLC is the bridge between the BIPV module and the LVDC grid. Its
 primary functions are to track the MPP and to increase the output voltage to
 the LVDC voltage level. There is no standardization yet on the exact voltage
 425 level of LVDC nanogrids in buildings but literature suggests unipolar voltages in

the range of 350 up to 400 V [41]. Note that twice this voltage can be available in a bipolar LVDC network to couple both low and high power appliances but the MLC is seen as a low power device and connected to only one network branch.

430 From a converter perspective, higher LVDC voltages are more challenging as the boost ratio has to increase. Converters with a low boost ratio or gain G achieve higher efficiencies and utilize a simpler converter topology. In practice, the border between high and low gain seems to be around $G = 5$ [42]. Below five, a standard boost converter can be used. Above five, more complex topologies
435 with transformers, coupled inductors, switched inductors or voltage multiplier cells need to be used [43]. When properly designed, these circuits still attain very high efficiencies but with a higher amount of components. This leads to increasing costs, lower power density and reduced reliability which are three important factors for BIPV MLCs.

440 When a 400 V grid is assumed and a standard boost converter is preferred, the BIPV output V_{MPP} voltage needs to be higher than or equal to 80 V. From Fig. 4 and Table 1, TF technology seems to be the most suitable technology from converter perspective due to the high output voltage and the resulting lower gains that are required to boost this voltage to the LVDC voltage level.
445 The limit of $V_{MPP} \geq 80V$ already occurs when the ratio S_{PV}/S_{tot} is above 30%. Also half cells are an interesting option, they reach the limit of 80 V when S_{PV}/S_{tot} is higher than 70%. A third possibility would be the use of shingled solar cells where cells partly overlap at the edges. They bring the opportunity of producing higher voltages with c-Si, at the expense of higher manufacturing
450 complexity of the PV generator [44, 45].

7. Conclusions

In this paper the concept of modular BIPV curtain walls was explained and the different aspects that relate to converter embedment are highlighted and investigated.

455 Firstly, the electrical output parameters of curtain wall BIPV modules are investigated by means of a case study façade where three different PV technologies (c-Si, half-cell c-Si and CIGS thin film) and different ratios between the glass area and the PV area of the BIPV module are evaluated. This analysis showed that a wide variety of voltages and currents can be present in a BIPV
460 curtain wall façade.

Secondly, an overview of commercially available MLCs is presented to check whether they are suited for embedment in façade BIPV modules. Therefore, they need to be compatible with the dimensional, thermal and electrical requirements. This analysis indicated that further progress is needed in MLC
465 development. It calls for a new class of MLC with appropriate form factor, voltage range, and temperature tolerance, in order to fit the use case in façades optimally. Using a LVDC grid would help greatly in simplifying these converters, reducing the number of components, and lowering the price.

The paper concluded with a discussion on standardization of BIPV MLCs
470 to further simplify and harmonize the design of the electrical installation and open the market for different converter design houses to make products that are easily interchangeable. Furthermore, TF or smaller c-Si cells seem the most suitable PV technology from a converter point of view. The high output voltage leads to lower gains resulting in more compact and more reliable converters.

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