The CIGS Building Integrated Photovoltaics: Financial Validity of Façade Applications under Current Technological and Market Conditions

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Abstract
The recent technological shift supported by the growing recognition of the public and policy makers of the renewable energy sources, fostered the employments on the uncharted markets. The energy industry increasingly affects the other sectors that were not directly related to the energy generation before. One of such examples is the construction industry which could benefit from the Building Integrated Photovoltaics. The objective of this paper is to analyze the current financial validity of the BIPV façade applications, under most recent CIGS technological advancements and market state. The topic is approached with the case study to assess the cost of investment and to learn the economic benefits through the installation life-cycle. The research indicated at economical validity of BIPV façade solution, with the IRR values reaching over 10% in case of the most optimal systems. In relation to traditional façade materials, the CIGS BIPV façade brings the substantial economic benefits to the investors, especially while being installed according to the best practices of PV system design (South, then East and West orientation). With the potential market pool of BIPV façade installations, the scale of CO_2 emissions avoidance should not be neglected. In the further research, the importance of valid business models could be investigated.

Keywords: CIGS, BIPV, Façade, Economic Benefit

1. Introduction

The 2019-2050's CAGR for cumulative global capacities is projected to reach 8.9%. In relation to its population, Europe leads the way in the PV transition. Only in 2019, the PV installation in Europe grew by over 100%. Regardless the past efforts, the goals of the Paris Agreement commitment, where Europe is expected to drastically reduce the CO2 emission, from 344g/kWh to 150 (65)g/kWh, might not be within the reach. In order to meet the requirements, the policies increasingly target the buildings' which are responsible for around 40% of total emission (IRENA 2019). It is especially important while construction market grows all over EU, driven by the rising prices of dwellings, immigration, and changing social structure. Moreover, the land limitations and public protests indicate the growing role of urban PV solutions. In the densely populated and wealthy areas of North Europe, residential PV stands already for majority of installations. The trend is only to be fostered with the Energy Performance of Buildings Directive which requires all new buildings to be nearly zero-energy by the end of 2020 (European Parliament and The Council of European Union, 2010). The low amount of energy that these buildings require comes mostly from renewable sources, including PV. As the natural following of technological and industrial advancement, the BIPV facade systems gradually gain on importance (PVSites, 2016). Due to the separate nature of PV and construction sectors, the sufficient proof-of-concept of BIPV should be delivered so the both parties could fully understand its advantages and challenges to disturb the long-established PV and construction processes.

2. Literature review

The growing importance of the BIPV facade application was noticed by the scholars. The topic is complex and covers numerous aspects. In top-down approach, one could enlist: market trends, the governmental policies, the equipment and solution classification; the performance of the systems; and their economic feasibility. As far as the market trends and policies are concerned, authors could point at the recent works of: Curtius (2018); Agathokleous and Kalogirou (2019); Osseweijer et al (2019); Defaix et al (2012); where scholars agree on the immense potential of the BIPV market (including facades) indicating, as well, the lack of market maturity which is caused partially by the lack of appropriate structural support and the insufficient understanding among the project developers. Further, in the solutions' classification, one should cite the findings of: Shukla et al (2016); Ceron et al (2013); Jelle et al (2012); or Frontini et al (2015). In relation to this research, the other authors often underline the difference between the mainstream and BIPV products. Unlike the large scale projects, the integrated solutions seem to be more technologically diverse due to the fact that the first generation silicon crystalline cells display the constraints in terms of application scope, customization, aesthetics and availability. Given that, after Frontini (2015) the next generation cells (here including thin-film CIGS) might stand for over 20% the BIPV applications (while for the mainstream the level does not exceed 4%).

The choice of the suitable technology is crucial to achieve the maximum of output, and therefore benefits from the BIPV installation. These, in the next stage, should be well examined and articulated since the lack of the sufficient number of reference projects (and studies) has been undermining the growth of the market. Although the scientific literature is still relatively scarce, one could point at some recent papers which authors found especially relevant to this research. Firstly, to provide the background about the energy yields generated under imperfect tilt angle conditions (as for BIPV façade), especially for the thin film technology, one could refer to the findings of: Sanchez and Izard; and Kumar et al. In their paper from 2015, Sanchez and Izard presented the test on amorphous thin-film (silicon technology) conducted in Spain. The performance factors, with respect to the installation of the perfect tilt angle, were estimated for: 66% (South facing façade), 49% (East facing façade), 38% (West facing façade), 51% (Southwest facing façade), 17% (North facing façade). The paper from 2019, published by Kumar et al, and dedicated to the CdTe cells (the second generation thin-film technology), focused on the tropical conditions in Malaysia and the obtained PR ratios reached: 71%, 70.53%, and 66.42%, for East, West North, respectively. Regardless of the relatively high Performance Ratios, the facades have a more stable production along the year. With some current net metering proposals, non-optimal orientations could even be more economical than the maximum producing orientation.

Shifting to the key objective of this research, the literature on the quantified economic benefits of the BIPV façade is to be provided. Here, authors focus on the very recent and complex analysis of Gholami and Røstvik (2019) who delivered possibly the most comprehensive results regarding the European market up-to-date. Their paper proposed the lifecycle cost analysis (LCCA) of BIPV system taking into consideration such factors as: saving in transmission line, lost power, saving in power delivery cost, saving form carbon tax, and saving in building envelope material cost. The most significant finding to emerge from this study is that even the north façade is economically feasible in some countries in Europe if all the environmental and societal benefits of the BIPV system are being taken into consideration. The results of this investigation also showed that the BIPV façade systems could not only serve as the building envelopes, but they also become the investment vehicles generating a stable source of income.

3. Methods

The objective of this paper is to analyze the current financial validity of the BIPV façade applications, under most recent technological advancements of thin-film CIGS technology and market state. Authors referred to the recent market data acquired from industry sources and during PV industrial exhibitions and employed it in the simulation regarding the location in Central Europe, Poland. Since the BIPV literature is relatively scarce (and data often outdated), while the industry progress relatively fast, authors hope that the research could significantly contribute to the understanding of importance of BIPV façade market offer.

The methodology includes three parts. Two parts consists on the data collection, which serves then to calculate the economic benefits (figure 1):

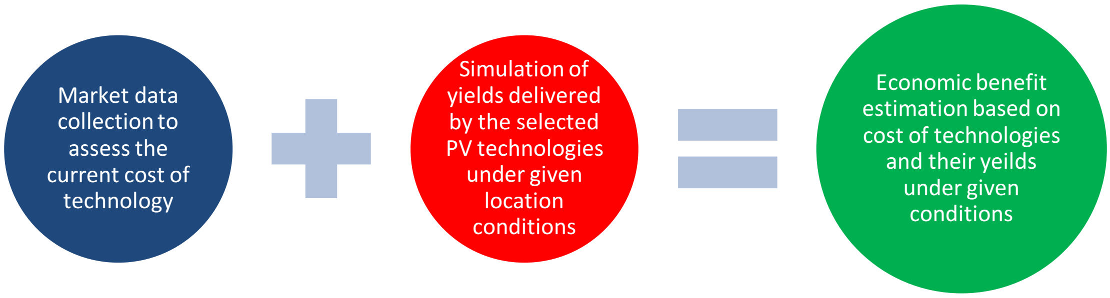

Figure 1. Research logic

3.1 Data

In the first part, authors grouped the data in regards to the major options employed in the façade solutions, traditional and BIPV. Authors delivered the actual and averaged market purchase conditions of: CIGS framed, CIGS frameless, and CIGS color printed offer. The data was acquired from industry sources and during PV industry exhibitions.

Figure 2. CIGS BIPV façade examples: CIGS frameless (left), CIGS framed (center), CIGS colored (right). (source: authors' database)

3.2 Yield estimation

In the second part, authors approached the yields that each of the above mentioned technologies would deliver once installed in the exemplary system in the location in Central Europe, Poland, Poznan (urban conditions of high building installation). The yields were estimated with the help of PVSol software accessible on its official website. For each type of solution, there were four separate simulation carried with the following assumptions: inclination angle 90 degrees; orientation to West, East, South, North; albedo of 20% (urban area); average rear ventilation; no soiling. The data regarding the yield of the colored modules was estimated according to the experiments carried on the colored solutions.

Table 1. PVSol yield simulations' assumptions.

Technolo	System	System	Power/surface	Façade	Alb	Soil	Rear
CIGS Color	4960	49.6	100	West South East North	20	non e	average
CIGS Frameles	4800	32	150	West South			

s				East North
CIGS framed	4800	32	150	West South East North

Source: collected data, PVSol.

3.3 Economic benefit estimation

In the third, final, part, authors proposed the assessment of the economic benefits from the BIPV façades, based on the Talavera et al. (2016) and Kryszak and Wang (2020) who analyzed the integration of the small PV system into the buildings in Spain with the variables of: NPV, IRR.

$$NPV = PW[CIF(N)] - LCC_{USP} \quad (1)$$
$$LCC_{USP} = PW[PV_{UIN}] + PW[PV_{OM}] \quad (2)$$

The net present value of an investment project is the sum of present values of all cash inflows and outflows related, over the period. Therefore, the parameter NPV equals the present worth of the cash inflows from the system ($PW[CIF(N)]$) minus the life-cycle cost from the user standpoint (LCC_{USP}) which stands for the sum of present value of the investment outflow $PW[PV_{uin}]$ and maintenance outflow $PW[PV_{OM}]$. From the NPV, one could derive that the IRR of the project which stands for the interest rate under the assumption of $NPV = 0$. The measuremnts of NPV and IRR serve to assess the investment in general terms and their values are often used as the argument for system purchase during the selling process of PV to the end-customers.

Since the goal of this research is to indicate on the economic benefits of the potential BIPV facade investments, in context of the replacement of the traditional facade materials, the calculations focused on the materials rather than delivering the accurate cost estimation of the whole process of installation. The labor cost was not included in the calculations, while the OPEX and BOS were roughly assumed based on the industry sources and existing literature.

4. Results and discussion

Table 2 discloses the data collected during the research. The costs of traditional façade materials are easily accessible, while they do not fluctuate much on the market. As it is presented, price range is wide with the fibrocement coming as the cheapest option. On the other hand, the high quality stone is the most expensive as it could reach over 800/m2. In recent years, the metal cladding gained on popularity, and its cost falls between 120 and 530Euro/m2.

Due to the limited number of suppliers of CIGS technology, and project oriented sale, the costs of facades modules were presented in absolute, estimated numbers, which are still highly accurate. As one could conclude, the PV CIGS cost is relatively moderate, especially as far as the regular, black solutions are concerned. The colored modules, due to the high cost of ceramic printing on the glass, are pricier however their cost could be still compared to the wood’s one.

It is important to underline that the traditional materials, although perceived as durable, do not offer any cash-flow from the investment, therefore they could be defined only as a cost incurred. On the other hand, the BIPV facades are, in fact, the investment vehicles which deliver the tangible economic benefits to the investors. Firstly, often, they bring the positive Net Present Value. Secondly, they leave the space for the more frequent renovations since their life-span reaches only 25 years (according to the warranties granted at the purchase), and, as it would be proved later in this research, the total pay-back of the investment capital is perfectly possible within this period.

Table 2. Facade materials data: traditional and CIGS BIPV.

Construction materials	**Cost/surface (Euro/m2)**	**NPV (Euro)**	**IRR (%)**	**Durability (years)**
Traditional materials				
Stone	130-820	negative	negative	long-term
Metal	120-530	negative	negative	75
Brick-ceramic	100-340	negative	negative	long-term
Wood	320-550	negative	negative	50
Fibrocement	40-220	negative	negative	30
PV materials				
CIGS framed	75	positive/negative	positive/negative	25
CIGS frameless	135	positive/negative	positive/negative	25
CIGS colored	300	negative	negative	25

Source: collected data, Frontini et al. (2015), Sousa and Sousa (2019), Grelk et al. (2007)

In the following part of the research, the actual economic benefit of BIPV façade was calculated. The results are to be found in table 3 below.

Table 3. Economic value estimation.

Technology	**Annual system yield/surface (kWh/m2)**	**Avoided CO_2 emissions (kg/year)**	**Module cost/surface (Euro/m2)**	**Module cost in the system (Euro)**	**Module with BOS (Euro)**	**NPV (Euro)***	**IRR (%)***
CIGS Color	40	974	300	14880	15680	-12206	-10%
	51	1273				-10457	-8%
	41	1000				-12008	-9%
	20	419				-15093	-16%
CIGS Frameless	77	1316	135	4320	5120	-177	0%
	100	1720				2049	3%
	79	1352				23	0%

	33	566				-4311	-11%
CIGS framed	77	1316				1743	4%
	100	1720				3969	9%
	79	1352	75	2400	3200	1943	5%
	33	566				-2391	-8%

*basic interest rate = 2,5%

In order to maintain the comparative value of the simulations, they were performed under assumption of the similar sizes of the systems: around 5kWp. As it was mentioned already, in the previous section of this article, authors did not take into consideration the installation costs, as they are relevant to both: BIPV and traditional materials, therefore authors assumed that they do not stand for the main and differentiating factor.

As far as the mainstream, framed modules, were concerned, the results indicate the high economic benefits to the investor. Apart of the North facing installation, the three other orientations provided a substantial positive NPV, with the IRR of at least 4% and maximum 9%. Such levels of IRR are unparalleled by the any risk-free financial investment. The frameless option provided less opportunity, however it is still highly beneficial to the investor. The South and West facing systems delivered the positive NPV while the yield cash-flows from the East facing installation almost managed to pay back the investment value. The maximum IRR reached 3% which could be related to the low-risk financial investments on some markets. The colored modules did not deliver the positive NPV. The IRR levels stayed negative and the high cost of the modules out-weighted the yield benefits. The economic assumptions of the colored modules simulation could be related to the traditional materials as they seem to be equally expensive, while they do not deliver the yield cash-flow. The core of the colored BIPV value lays rather in its aesthetics and eco-friendliness, rather that the purely positive economical metrics.

It is worth to underline the additional benefit of BIPV facades reflected in the avoided CO_2 emissions. Although it has not a direct financial impact on the investment assessment, one could not exclude such impact in the future. In order to confront the findings of this paper, table 4 presents related results derived from the other scholars' publications.

Table 4. Related literature review and results

Study	**Study period**	**Country**	**Methodology**	**Conclusions**
Facade functinality				
Sánchez and Izard (2015)	January 2011-November 2012	Spain	Photovoltaic facade with a south-west orientation and an architectural model of a building with the facades in the	Although the annual energy production for the facades and the roof is between 50% and 76% of an optimum angle installation, the facades have a more stable

			cardinal points, covered with PV.	production along the year (the experiments were based on thin-film cells). With some current net metering proposals, non-optimal orientations could even be more economical than the maximum producing orientation.
Kumar et al (2019)	1 year of model study	Malaysia	The model based the performance research of thin-film CdTe (thin film) building BIPV arrays proposed as a flat roof, and façades oriented in east, west, and north under the tropical weather conditions	The variation in performance ratio (PR) for each façade oriented in different directions and the roof (2.3 kW façade in east and west, and 5.5 kW façade in north): 71%, 70.53%, and 66.42%, respectively, and corresponding energy losses are −28.8%, −29.4%, and −33.6%.
Jannuzzi and Silva (2012)	1 year of model study	Brazil	The generation provided by the North, East, West a-Si (c-Si thin-film) facades simulated and compared with optimal angle to calculate the performance losses with software employment.	PV generation decreases considerably (40 to 45%) when the modules are installed on vertical surfaces (buildings facades). The optimum generation periods shape differently compared to the perfect orientation and tilt angle installations.
Economic benefits				
Gholami et al (2019)	Long-term simulations	China, Brazil, Italy, Bahrain	The Life Cycle Cost Analysis based on NPV metrics, extended by the societal benefits. Simulation study on actual cases.	With the societal and environmental benefits of the implemented system, replacing conventional façades and roof building materials with BIPV modules will become economically more feasible. With the traditional Payback Period and NPV metrics, the BIPV façade is still very attractive form of investment and the periods are counted below 10 years in the high irradiation locations.
Gholami	Long-te		The Life Cycle Cost	BIPV system as a building

and Rostvik (2020)	rm simulations		Analysis based on NPV metrics, extended by the societal benefits. Simulation study across European countries with the highly detailed sensitivity analysis.	envelope material for the whole building skins could reimburse not only all the investment costs but also become a source of income for the building. Even the north façade is economically feasible in some countries in Europe if all the environmental and societal benefits of the BIPV system are being taken into consideration.
Gholami et al (2020)	2016-2019 data set based research, long-term simulations	Norway	The Life Cycle Cost Analysis based on NPV metrics, extended by local market characteristics.	BIPV façade with the peak power of 127.5 kW is economically feasible with a DPP of 22 years, IRR of 6%, cumulative NPV of 478,934 NOK and LCOE of 1.28 NOK/kWh. With an average annual solar irradiance on the system of 707 kWh/sq.m., the average annual electricity production is 40 kWh/sq.m.
Evola and Margani (2016)	long-term simulations	Italy	The Life Cycle Cost Analysis of block renovation in Italy, extended by the technological comparison.	CIGS and c-Si are economically comparable, a-Si modules are currently not profitable. Without the incentives, the PBT would reach about 14-15 years, with slightly higher values for the c-Si. Even a south-facing facade presents a potential energy yield that is around 30 ÷ 35% lower in comparison with the optimal slope.
Oon and Ng (2017)	Short period simulation	Singapore	Electricity generation analysis supported by with the economic benefit perspective.	The cost/m2 of CIGS solar PV panels (without the BOS) is just a little bit more expensive compared to ceramic tiles. The cost of the entire CIGS system is potentially cheaper than aluminum composite panel as cladding material for facades with large areas.

5. Conclusions

The objective of this paper is to analyze the current financial validity of the BIPV façade applications, under most recent CIGS technological advancements and market state. The topic was approached with the case study to assess the cost of investment and to learn the economic benefits through the installation life-cycle. Authors reached the following conclusions:

1. In relation to traditional façade materials, the CIGS BIPV façade brings the substantial economic benefits to the investors, especially while being installed according to the best practices of PV system design (South, then East and West orientation).
2. With the potential market pool of BIPV façade installations, the scale of CO_2 emissions avoidance should not be neglected.

In author’s assumptions, the further research could be directed towards the novel and effective business models, to channelize the already existing technological prospects of merging the construction and PV industries.

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