LIFE CYCLE ASSESSMENT OF
BUILDING INTEGRATED PHOTOVOLTAIC SYSTEMS

Feasibility study on a methodological approach to assess the environmental impacts of BIPV systems

T15 Subtask D: Environmental assessment of BIPV systems

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Abstract

The question of accelerating the penetration of BIPV products in the global market of renewables also relies on the environmental perception of BIPV by building owners. Indeed, several studies are addressing the overall installed capacity of BIPV at world and European level. With roof surface between 8 to 36 m^2 per capita in the world, estimations of capacity worldwide indicate that BIPV can cover 20 % of the electricity demand. It can reduce the load on the grid and provide about 30 % of the electricity needed by buildings.

At the same time, BIPV installation is never optimum for energy production and presents limited profitability. An important motivation of building owners is their environmental awareness, but green washing and misleading declaration is often weakening environmental communication.

Elaborating a reliable and consensual environmental assessment framework is a positive response to mistrust. The two conditions of success of such an effort are: (1) elaborating *rules allowing comparative assessment* in coherence with the environmental reality of the product and with respect to existing international framework; (2) ensuring that the proposed method is *easy to use* with limited expertise and time requirements.

The work achieved in T15 STD demonstrates that these two requirements can be fulfilled with simple rules that fully respect the international framework of Life Cycle Assessment (LCA). For that purpose, 11 case studies are assessed with the LCA rules elaborated during this work.

In order to ensure a broad variability of the situations, the BIPV case studies are from 9 different countries and cover numerous different systems. The case studies environmental performance assessment is conducted with the aim of enabling a first environmental screening with only a limited number of easily-accessible parameters. A first assessment can thus be conducted easily and a more detailed appraisal can then be gradually done with more and more specific data to get more accurate results. Results are then presented in detail, demonstrating the applicability of Life Cycle Assessment for assessing and comparing different BIPV systems. Five PV technologies are considered. Mono-crystalline silicon modules present a carbon footprint ranging from 251 to 341 $kgCO_2eq/m^2$ and an efficiency ranging from 15.2 to 20 %. Hybrid PV thermal modules are based on a mono-Si technology. They feature a carbon footprint ranging from 380 to 400 $kgCO_2eq/m^2$ and an efficiency of 15.4 %. Multi-crystalline silicon BIPV modules present a carbon footprint ranging from 262 to 334 $kgCO_2eq/m^2$ and an efficiency varying from 14 to 17.3 %. CIGS modules are used for two case studies, their carbon footprint is around 190 $kgCO_2eq/m^2$ and their efficiency ranges from 11.8 to 13.8 %. The case studies using amorphous silicon BIPV present a carbon footprint of 135 $kgCO_2eq/m^2$ and an efficiency of 7.6 %. Following the classifications developed in section 3, three categories of BIPV systems are assessed, comparing BIPV and a conventional building skin, and considering both materials and energy. Opaque roof BIPV are tested with 7 different situations and present carbon emissions which are between 34 and 78 $kgCO_2eq/m^2$.year. Opaque façade BIPV are addressed with 19 different situations and present carbon savings which are between 14 and 121 $kgCO_2eq/m^2$.year. Transparent façade BIPV are only

considered with 8 different situations and allow carbon emissions which are between 2.5 and 24 $kgCO_2eq/m^2$.year.

The main results observed can be summarized as follows: 1) The large diversity of BIPV systems requires to rely on a classification of BIPV; 2) Environmental performances shall be addressed at-the-system level and not at-the-module level, even if it requires to make assumptions for BIPV prior to their installation on the buildings; 3) BIPV's carbon footprint can be reduced by optimizing their design or using green electricity during the production process of the module (or its sub parts); 4) BIPV's optimum environmental performance is obtained when connecting an electricity network with a high carbon footprint per kWh; 5) Environmental assessment (and especially the carbon footprint including the use phase) need to be quantified even at the early BIPV design stage, way before their installation on buildings. Indeed, among all the configurations of BIPV systems tested throughout the project, some may have more carbon dioxide emissions during their production than the difference in emissions due to the substitution of the conventional building component, even after being used throughout the indicated lifetime provided by the manufacturer beside the warranty period.

More generally, the work done can be put in perspective with the meaning of ISO 14040-44 which is stated in its introduction: "LCA can assist in: (1) identifying opportunities to improve the environmental performance of products at various points in their life cycle; (2) informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign); (3) marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration)." The rules proposed enable performing Life Cycle Assessment of BIPV with respect to the meaning and the key aspects of the ISO 14040-44 standard.

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Foreword

The International Energy Agency (IEA), founded in November 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The IEA Photovoltaic Power Systems Programme (PVPS) is one of the collaborative R&D Agreements established within the IEA and, since its establishment in 1993. Among the tasks addressed by PVPS, T15 especially focuses on Building Integrated Photovoltaic systems.

The framework of Task 15 is presented in [http://www.iea-pvps.org/index.php?id=task15]. T15 objective aims at "Enabling Framework for the Acceleration of BIPV". A more detailed presentation is provided "The objective of Task 15 is to create an enabling framework to accelerate the penetration of BIPV products in the global market of renewables, resulting in an equal playing field for BIPV products, BAPV products and regular building envelope components, respecting mandatory issues, aesthetic issues, reliability and financial issues". Among the work planned, Subtask D addresses environmental assessment of BIPV systems. In this subtask, the environmental benefits of BIPV are investigated, resulting in a methodology for the environmental assessment of BIPV products, comparable with the environmental assessment of regular building envelope components, bridging the gap between PV LCA and building material assessment."

We especially acknowledge the ADEME [Agence de l'Environnement et de la Maîtrise de l'Énergie] for funding and supporting the work. The ADEME is funding Cycleco for leading STD and exploring feasibility of Life Cycle Assessment (LCA) of BIPV products with sub-task participants. Considering the international context of the project, the work shall be performed with respect to the existing international standards of LCA ISO 14040-44. The LCA method developed shall enable a transparent and reliable comparison between BIPV and conventional building envelope components.

1 Introduction

Worldwide energy demand is continuously increasing (International Energy Agency 2019). The share of electricity in the energy consumed is more and more important and electricity consumption increases by 4 % in 2018 (Ibid.). Despite a greater share of renewable energy in the electricity mix, two-thirds of worldwide electricity continues to stem from fossil fuels, hence being an obstacle to carbon footprint reduction. In 2018, the increase in GHG emissions due to electricity was 2.5 %.

Concurrently, a majority of governments adhere to worldwide climate change mitigation, as well as an 'increasingly eco-conscious' population (United nation for climate change 2016).

As a result, there is therefore a conflict between rising electricity needs and environment protection. The political answer is reduction of the electricity's carbon footprint. The way to achieve it is to produce electricity with renewable resources.

Among all renewable electricity sources, solar power offers several advantages since it is present everywhere and combines both rather good predictability and low-cost production. These features foster a large deployment of solar PV, illustrated by the installation (particularly in Asia) of numerous large ground-mounted power plants. However, such plants are facing two limitations that are of growing concern: land use competition and expensive electricity networks (construction and maintenance).

Building-Integrated PV (where building components fulfil building function and energy production) and Building-Applied PV (where the building is simply used as a support for PV) offer very promising solutions, avoiding land use conflicts and already connected to the electric network. In addition, buildings are also an important place of electricity consumption (Choi et al. 2019; Tejero-González et al. 2019; Cornaro et al. 2017; Kammen and Sunter 2016; Hermelink et al. 2013). As a result, many countries have investigated the possibility to install electricity-producing PV on buildings' roofs and façades (Petrichenko, Ürge-Vorsatz, et Cabeza 2019; Vulkan et al. 2018; Asaee et al. 2017; Bäuerle et al. 2017; Defaix et al. 2012; Ordenes et al. 2007; Eiffert 2003; Nowak et al. 2002). The easiest and least expensive way was to develop BAPV even if it does not always fulfil aesthetic requirements.

BIPV is an integral part of a building's skin. It is a building component integrated on roofs (opaque roofing or skylight) or façades (semi-transparent or opaque) (Wilson et al. 2018; Zhang, Wang, et Yang 2018). This requirement makes BIPV typically more complex and expensive since it has to meet building and energy systems' standards, as well as aesthetic prerequisites. At the same time, building integration also forces location, tilt and orientation of the BIPV system which typically results in a diminution of the PV overall electricity production. Compared to ground mounted PV or BAPV (Building-Applied PV) which can be economically profitable since it is always installed in the optimum situation for electricity production, BIPV always presents lower profit due to sub-optimal installation or low maintenance. The main motivation for installing BIPV is to generate electricity with low GHG emissions and thus possibly contributing to lower the GHG emissions of the country's grid mix. In this context, any confusion in communicating environmental performances of BIPV products is counter performing. The trends in BIPV installed capacity reflects this confusion. Despite being a renewable electricity source, close to the consumer with in some cases a cost similar to the network electricity, BIPV capacity evolution can impede ecological transition's expectations like the EU targets for 2030. While an installation growth of 18 % was predicted for 2015 to 2019 with very similar figures at European and global scale, (PVSITES 2016; Frost and Sullivan 2010), it has been now reduced to 10 to 12.2 % (Panos et Margelou 2019; Vickstrom 2016; Technavio 2016). Even with huge installation capacity worldwide (Defaix et al. 2012; Eiffert 2003; Nowak et al. 2002), a cost reduction of PV over time and a fast increased environmental awareness of building owners, a reduced growth of BIPV installations is likely to limit the availability of renewable energy, and subsequently the ambition of the energy transition by 2030[1]. A clear and transparent communication for environmental assessment of BIPV is needed in order to build up trust with building owners.

In this context, the aim of task 15 to overcome the barriers in order to enable the acceleration of the BIPV market is fully relevant. Among all barriers, environmental assessment of BIPV is under focus with subtask D. The role of the subtask is to explore the strength and limitations of environmental assessment of BIPV systems and to propose solutions which allow comparing BIPV with conventional solutions and between BIPV systems with reliable and transparent results.

The specificity of BIPV is the multi-functionality. BIPV satisfy both a building function and an energy production function. This is one of the most complex issues to address in Life Cycle Assessment. A review of 350 scientific publications for environmental assessment of PVs since 30 years reveal 170 studies referring to the LCA (life Cycle Assessment) method. Among these studies, nearly 60 articles refer to BIPV with a geographical coverage of 15 countries. Most of the studies rely on the LCA ISO standard 14040-40. In spite of this effort of convergence using the same standard, the first observation is the huge variability of the results presented, which can vary sometimes by more than a factor 10 even with very similar systems under study (Ludin et al. 2018; Biyik et al. 2017; Wong, Royapoor, and Chan 2016). Two reasons explain this variability, first of all, the large flexibility of the ISO standard for elaborating LCA (the standard remains open for a number of modelling assumptions); and second the specificity of BIPV which -as a multi-functional system- makes it far more complex to address in Life Cycle Assessment. Clear indications are needed by scientists to perform LCA of BIPV. Defining the functional unit, describing and quantifying the additional function, selecting the system perimeter, etc., are parameters that need to be defined.

[1] As an example, energy transition EU targets are ambitious. Depending whether a reduction of energy consumption of 1 % can be reached between 2020 and 2030, the expected energy demand in 2030 will be between 1 450 and 1 600 MTo (Eurostat 2019). Considering an electrification reaching 28 % of total energy and 56 % of renewable energy in the EU mix (Buck, Graf, et Graichen 2019), the demand in renewable electricity will be between 1 700 and 1 900 TWh in 2030. Assuming a BIPV growth of 10 % until 2030 (Technavio 2016), we can expect to reach 23 TWh of installed capacity. This represents less than 3 % of the overall BIPV installation capacity (Defaix et al. 2012) potential and will contribute to only 1.2 % of the total renewable electricity.

2 Objectives

The objective of the work is to explore the applicability of Life Cycle Assessment for assessing and comparing BIPV's environmental impacts, with or without the system being integrated into a building and with respect to the system's multi-functionality.
The main methodology issues are identified and discussed. Whenever possible, key parameters (necessary for assessing BIPV's environmental performance) are sorted out and discussed.
The work is organized around the examination of eleven case studies from nine different countries. BIPV case studies cover three building solutions (opaque roof, opaque façade and semi-transparent façade) and five PV technologies (mono-Si, multi-Si, a-Si, CIGS and hybrid PV-T).

3 Environmental assessment method

The definition of BIPV is typically given at the product or at the system level (EN - European Standard 2016; Eiffert 2003). It, first of all, rests on the product's or the system's multi-functionality, which differentiates itself from BAPV. Beyond the definition, BIPV covers a large diversity of building solutions, technologies, mounting types and electric integrations into the building and the grid. A classification, aiming at facilitating environmental modelling (as well as comparability) between BIPV is explored.

3.1. Definition and classification

The definition of BIPV proposed by IEA-PVPS Task 15, Subtask C (Wilson et al. 2018) members is reported below.
"*A BIPV module is both a PV module and a construction product, designed to be a building component. A BIPV module is the smallest (electrically and mechanically) non-divisible photovoltaic unit in a BIPV system which retains building-related functionality. If the BIPV module is dismounted, it would have to be replaced by an appropriate construction product.*
A BIPV system is a photovoltaic system in which the PV modules fulfil the definition above for BIPV products. It includes electrical components (needed to connect PV modules to external AC or DC circuits) and the mechanical mounting system (needed to integrate the BIPV modules into the building.")
The definition proposed in T15's report is more detailed than the definition of the EN 50 583 standard - especially concerning the building's function - and includes modules and systems in the same definition. The definition of BIPV modules according to the EN 50 583 standard is presented below.

"Photovoltaic modules are considered to be building-integrated, if the PV modules form a construction product providing a function[2] *as defined in the European Construction Product Regulation CPR 305/2011. Thus, the BIPV module is a prerequisite for the integrity of the building's functionality. If the integrated PV module is dismounted (in the case of structurally bonded modules, dismounting includes the adjacent construction product), the PV module would have to be replaced by an appropriate construction product.*
The building's functions in the context of BIPV are one or more of the following:

- *mechanical rigidity or structural integrity*
- *primary weather impact protection: rain, snow, wind, hail*
- *energy economy, such as shading, day lighting, thermal insulation*
- *fire protection*
- *noise protection*
- *separation between indoor and outdoor environments*
- *security, shelter or safety."*

A BIPV product is a part of the building's skin and can be integrated in many different places. One of the most common practices is the installation of PV modules in tilted roofs, but they can also be placed on flat roofs or façades. A distinction shall be made between opaque modules (used for roof or façade cladding) and semi-transparent modules (that can be used for curtain walls, skylight roofs, verandas, windows, etc.). A BIPV system can either be connected to the grid or be a stand-alone system, with or without electricity storage.
Beyond these definitions, BIPV's classification is crucial to enable an accurate comparison of their environmental performance. Several scientific articles have explored the possible classification of PV and BIPV systems, based on their technology, their efficiency, their age (1st versus 2nd generation), their novelty, etc. in order to facilitate the elaboration of a comparative framework (Shukla, Sudhakar, et Baredar 2017; Biyik et al. 2017; Ekoe A Akata, Njomo, et Agrawal 2017; Baljit, Chan, et Sopian 2016; Basant Agrawal et Tiwari 2010). The classification retained is based on the systems' function (mainly distinguishing roofs from façades and opaque systems from semi-transparent systems).

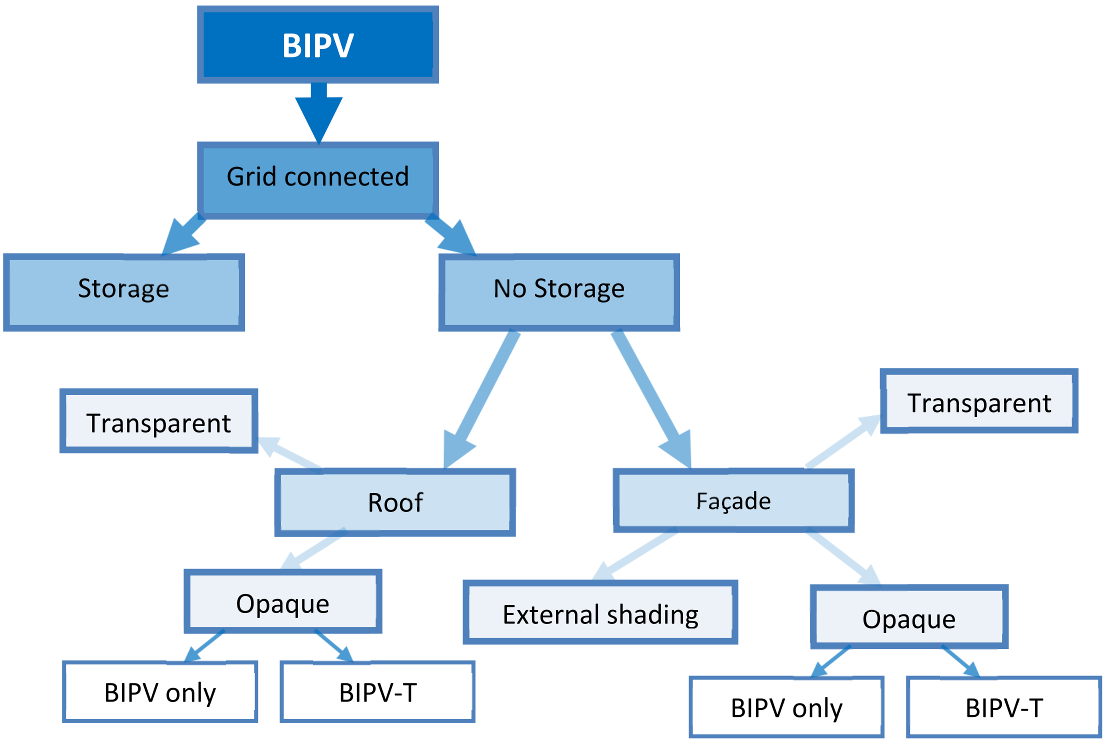

Figure 1: Classification of BIPV systems (defining the product categories considered in the study). "BIPV only" refers to BIPV only producing electricity, "BIPV-T" refers to BIPV producing both electricity and thermal energy.

The classification is covering large groups but STD works focus on grid-connected systems and do not consider electricity storage. Only opaque roofs and façades and semi-transparent façades are included in the scope. No case studies are available in T15 STD as for semi-transparent roofs are concerned, as well as no case studies for external shading systems which are installed on the façade. Thus, only three categories are covered (opaque roofs, opaque façades, semi-transparent façades).

3.2. Life Cycle Assessment method

Life Cycle Assessment (LCA) is an environmental appraisal method clearly described in the ISO 14040-44 standard (ISO. 2006a; 2006b). It is the most commonly used method for PV systems' environmental assessment. The analysis of the case study is conducted thanks to LCA. The main LCA methodological issues (which need to be defined in order to ensure BIPV study comparability) are described in the corresponding section of the report.

The LCA study shall commence describing the system's function and the functional unit (FU). The BIPV system is multi-functional, thus the "*function*" corresponding to the functional unit and the "*additional function(s)"* shall be defined[2]. Since PV is integrated in the building, the "*function*" of the system is the building function. Indeed, in several situations, the BIPV system is kept in the building even if it does not produce energy anymore (provided that the building's function is still fully fulfilled). On the contrary, if the building function is no longer fulfilled, BIPV is removed even if it still produces energy. Therefore, energy production is considered as the *"additional function"* (which is one function if only electricity is produced and two functions if hybrid BIPV produces both electricity and heated air or water). The functional unit (considered for the case studies) is "*1 m2 of building skin protecting the building during one year, provided that building and energy production functions are fulfilled during 30 years*".

Based on this functional unit, two (or more) comparison scenarios can be easily defined as the scenario of 1 m^2 of BIPV system compared to 1 m^2 of conventional building skin (made with conventional material). After ensuring that the main function is fulfilled, all system differences (in terms of inputs/ outputs) contribute to differentiate the two scenarios.

End users of the study results can be BIPV manufacturers, retailers, or architects who wish to quantify the environmental performance of BIPV systems within a comparative framework using the Life Cycle Assessment.

Life Cycle Assessment can be conducted at any step of the product's development and at any level of detail. Table 1 (below) presents the scope of the study.

[2] ISO 14040-44 distinguish the «addtional function» and the «function» of the system. For matter of clarity in the terminology of the report, the term «main function» in the report refers to the «function» of the ISO.

Table 1: Product under study and level of specific data available depending on the situation of the product. Each cell represents a possible level for assessing the BIPV, the information in the red box represents the studies that are applicable to this work. Since only the BIPV system is addressed in this report, the type of data required are completed only for these cells.

	Design	retail	installed	Short-term feed back	Long-term feed back
Cell	Not covered	Not covered	Not covered	Not covered	Not covered
Module	Not covered	Not covered	Not covered	Not covered	Not covered
BIPV System	Important assumptions	Statistical data	On site estimation	Specific data for electricity	Detailed data
Building	Not covered	Not covered	Not covered	Not covered	Not covered

Table 1 shows that the BIPV system is assessed as a building product separately from the building. The building considered in the study is only here to illustrate tilt, building orientation and location specificities. For tilt, the BIPV system could be assessed even with default data. Hence, the BIPV system can be assessed at any stage of its development, from its early design to a long-term study after its installation. For early stage assessment, when specific data are not available, generic or statistical data should be considered.

In terms of system boundaries, the product considered is a Building-Integrated Photovoltaic system (BIPV system) used as a complete building component. All processes necessary for the integration of the BIPV system are included (i.e. production steps, grid-connexion subsystems, building structure and building skin, use phase including inverters replacement, electricity generation and related, systems' end-of-life including collection transportation and waste management). No benefits are associated with waste (energy recovery and recycling benefits are not included in the system).

The data sources for modelling the different case studies are, as much as possible, specific data (which are data made available by the BIPV manufacturer and/or the building engineer). Nevertheless, depending on the case study we are focusing on, generic data are sometimes used. The following data sources are used: irradiation data are typically estimated using the PVGIS software (Huld, Müller, et Gambardella 2012). Electricity mixes are based on statistical data from the ENTSOE organisation for year 2016 (ENTSOE 2016). For outside-ENTSOE countries, data stem from the International Energy Agency and national statistics. Life Cycle Inventory data are also needed to model the system. Ecoinvent 3.5's 'alloc-def' market data is systematically used for generic data, enabling a consistent modelling. This is for example the case for modules, inverters, mounting systems and conventional material modelling.

The environmental impacts of case studies are calculated for all impact categories of the ILCD 2011 method using the characterisation models proposed by the ILCD (European Commission 2010). The current report focuses on the climate change impact. In order to facilitate results' interpretation, carbon payback time (CPBT) can be used to describe BIPV's environmental performance (Payet et Greffe 2019). It is the ratio between carbon emissions (generated during BIPV production) and annual carbon emissions (difference in emissions due to the BIPV system during the use phase). Results are expressed in years and indicate the time it takes for BIPV to compensate for the Green House Gas (GHG) emissions released during its production.

The question of multi-functionality is typically part of the scope and goal's definition. Nevertheless, BIPV's environmental performance modelling strongly depends on this issue. Therefore, instead of covering this issue in very few words, it is thoroughly explained and discussed in section 4.

3.3. Modelling parameters

The calculation of BIPV's energy and environmental performance relies on quantified descriptors (module, system, situation, connection to the network, grid mix specificities description). Approximately thirty parameters are typically used for such a calculation. All parameters are studied in detail in the case studies. These parameters enable the calculation of: irradiation received by the system, energy (electric or thermal) produced and environmental benefits due to the connection to the electricity grid.

The irradiation received by the system depends on the location, the tilt, the orientation and the environmental conditions of the installation (Zhang, Wang, et Yang 2018; Hsu et al. 2012; Blanc et al. 2011; Pacca, Sivaraman, et Keoleian 2007). For BIPV, all these aspects are engendered by the building itself. Irradiation conditions are therefore never optimal since the tilt depends on the roof or the façade, orientation depends on the position of the building, and urban-area buildings are more prone to dust and shadow for example. Irradiation (considering location, orientation and tilt) can be obtained using software tools. Nevertheless, monitoring measures can substantially differ from modelling data and are preferred when available. If only monitoring data are available, annual data typically used but shorter periods are preferred whenever available. It can be monthly data (which avoids seasonal bias) or hourly data (which avoids daily bias). The level of detail often depends on the statistical data available.

The PV system exposed to light produces electricity. The amount of electricity produced depends on the overall system's efficiency. Many parameters have to be considered when appraising the losses of the system. Indeed, cell and module efficiency, power conditioning system, stand-by mode, module temperature, DC-AC conversion, system breakdown, packing factor, module degradation over time, system lifetime, etc. all constitute parameters that affect the efficiency of the light conversion (received by the module) in output electricity. A majority of these parameters is included in the performance ratio which can be based on monitoring, statistical data or empirical estimates. In our case study, monitoring data are rarely available. All parameters are therefore integrated inside a performance ratio based on empirical data (IEA-PVPS T2-06:2007 2007; Y. Wang et al. 2018; Martín-Chivelet et al. 2018; Lee et al. 2018; Schweiger et al. 2017). The time step of the energy production data is determined by the availability of the irradiation data. Beyond the performance ratio, the system's components replacement (based on actual or estimated lifetime) shall be used. As an example, the lifetime of an inverter is assumed to be 15 years) (Frischknecht, R., et al. 2020).

After having calculated energy (electric and possibly thermal) production, we shall model differences in carbon emissions. Indeed, comparing a BIPV system with a conventional building skin also requires quantifying the environmental impact of (equivalent) electricity produced with the conventional building's skin. For this purpose, it is assumed that the same amount of energy (calculated as an output of the BIPV system) is produced by the grid in the conventional situation. The quantification of the impacts of the kWh from the grid requires to choose the relevant electricity network (also called electricity grid) and to define the electricity means (composing the kWh produced with this network commonly called production mix with imports). A calculation, covering each energy source and using a LCI database such as ecoinvent, enables to calculate the environmental burden of 1 kWh of electricity from the grid. Multiplying it by the number of kWh produced by the BIPV system gives the value of the environmental impact of the energy that would be used in the scenario assessing a conventional building component, also called conventional scenario.

3.4. Limitations

A clear distinction is made between Life Cycle Assessment (LCA) and Life Cycle Inventory analysis (LCI). This work is strictly limited to LCA. The rules and indications provided here are not aimed for Life Cycle Inventories. Any observation relating to LCI methodological aspects (development, format and dissemination) are out of the scope of this work. As an example, multi-functionality can be handled differently in Life Cycle Inventory analysis.

Life Cycle Assessment aims at assessing products environmental performance and expressing the results in terms of impacts on the environment. The validity of the LCA results are restricted to the frame of the study and entirely depends on the assumptions of the study. Therefore, the results are not intended for reuse as inputs for other LCA studies.

The work strictly considers grid-connected systems that are a part of a roof or a façade without storage. Therefore, stand-alone BIPV systems and electricity storage are out of scope.

Similarly, since no case study addresses semi-transparent roofs, only three categories remain. They are: opaque roofs (with BIPV or BIPV-T), opaque façades and transparent façades.

BIPV systems' end-of-life management is included in the study, but no material bonuses are included in the system. Indeed, recycling is considered as a steady state situation, where the recycled material entering the system corresponds to the recyclable material leaving the system. As a result, there is no environmental benefit overestimation due to end-of-life recycling.

4 Multi-functionality issue

4.1. General presentation of multi-functionality

The following section discuss the multi-functionality throughout the Life Cycle Assessment of BIPV: comparing a functional unit based on building skin's square meters and a functional unit based on kWh of AC power.

Functional unit based on the building function

In case of BIPV, the *main function* is the building function. Indeed, BIPV sometimes remain on buildings even in the absence of electricity generation (e.g. inverters breakdown, shade, dust, snow, etc.). In the opposite, when the building function is not fulfilled, the product is immediately replaced. If the main function is the building function, then the functional unit shall be addressed as a building material unit. As an integral part of the building's skin, the typical unit for BIPV is one m^2 of building skin during 30 years. In this particular case, the additional function is energy production. This function is then addressed as the quantity of electricity produced by the square metre of BIPV during 30 years. When compared to a conventional system, both functions shall also be fulfilled to ensure comparability. One square metre of BIPV during 30 years and producing X kWh is comparable to one square metre of building skin covered by a conventional material PLUS X kWh of energy produced by a conventional system. The system boundaries are therefore defined with respect to the ISO 14040-44 requirement which specifies "*Wherever possible, allocation should be avoided by expanding the product system to include the additional functions related to the co-products, taking into account the requirements of 4.2.3.3.*"

Comparing BIPV with conventional material in terms of carbon footprint per m^2 of BIPV

Also, as presented in the case study report, the carbon footprint of conventional materials used for building skin range from 0.7 to 7 $kgCO_2eq/m^2$.year (for cement tiles and aluminium plates, respectively). The carbon footprint of BIPV systems ranges from 4.5 to 13.5 $kgCO_2eq/m^2$.year (for an a-Si BIPV roof and a Hybrid mono-Si roof, respectively). As an indicative average, the conventional material features a carbon footprint which is 5 times lower than BIPV with far more variability.

Comparing BIPV's carbon footprint with electricity's carbon footprint in kWh

At the same time, the case studies presented in the report indicate that the electricity mix can vary from 22 to 705 gCO_2 eq/kWh (for Norway and Alberta respectively) and that the energy produced by BIPV ranges from 50 to 278 gCO_2eq/kWh (for Zaragoza multi-Si BIPV and Fronius eastern façade mono-Si BIPV respectively). There is a factor of 30 (carbon footprint variability) for the electricity mix with an indicative average around 600 gCO_2eq/kWh, while there is only a factor of 5 for GHG emissions with an indicative average around 110 gCO_2eq/kWh.

Key aspects of multi-functionality

BIPV is per definition a multi-functional product. Therefore Life Cycle Assessment of BIPV requires to have clear understanding of multi-functionality. As presented above, two modelling options are possible. For T15. A functional unit based on square metre of building skin allows comparison of the carbon footprint with other material useful for a building skin. A functional unit in kWh of energy produced allows comparison of the carbon footprint with other systems producing energy. The later comparison always presents lower environmental performances for BIPV. Ground mounted PV or BAPV (Building Applied PV) are always optimized for electricity production, but BIPV always present sub-optimal installation (orientation, tilt, location, shading, cooling, etc) and lower maintenance (cleaning, inverter breakdown, etc). At the end, it shows that it is more efficient in terms of electricity production to put PV in fields or on well oriented existing structures. Other motivations for installing BIPV can be landscape competition, electricity network optimisation and aesthetic requirements. And these three aspects are not reflected by a comparison based on the kWh. On the opposite, using a functional unit based on the square metre of building skin better reflects issues related to the surface available and the aesthetic, the network integration being still not addressed in the scope since the network is considered to be the same for both scenarios.

A comparison between BAPV and BIPV is still an issue because BAPV is not multi-functional. So the comparison can only be made on the production of energy. Two recent studies (W. Wang et al. 2016; Kumar, Sudhakar, et Samykano 2019) indicates that BAPV produce more electricity than BIPV in similar configuration. The first study indicate that the actual efficiency of PV increase from 10.8 to 11.2 % from BIPV to BAPV, and the second study shows that performances of BAPV are 4 % higher than BIPV for cSi; 2 % for CIGS and 0.2 % for CdTe. Based on these assumptions, we can model a variant with case studies in T15 comparing the potential increase in electricity production assuming BAPV installation instead of BIPV and comparing it with the carbon footprint of material saved thanks to BIPV. Results indicate that the carbon footprint of conventional material is in between 0.5 and 10 % of the environmental benefit of increasing electricity production with BAPV. The highest value is obtained with CIGS modules (only 2 % increase) as PV and aluminium plates as substituted material. In that extreme case, the impact of material avoided represents 30 % of the environmental benefit of the overproduction of electricity. Also beyond these calculation, we can also observe that only a small part of the building surface available for BIPV offers opportunities for BAPV. For reasons of efficiency and profitability, BAPV is only install on the optimum surface for solar irradiations.

4.2. Applying Multi-functionality to T15 STD case studies

The ISO guideline gives clear indications on what has to be included in the system's boundaries. All system's inputs, processes and outputs shall be included. Indeed, in case of multi-output systems (when a product fulfils several services for example), the overall environmental performance result can be strongly affected by outputs. This is likely to completely change the results and the ISO standard adds this requirement: *"the deletion of life cycle stages, processes, inputs or outputs is only permitted if it does not significantly change the overall conclusions of the study. Any decisions to omit life cycle stages, processes, inputs or outputs shall be clearly stated, and the reasons and implications for their omission shall be explained."*

When multi-functionality is identified, the ISO standard also gives indications on how to resolve this issue. ISO requires to apply a stepwise solution and the first step is the *"subdivision of the system if possible"* OR *"expanding the system in order to include the additional functions related to the co-products."* As mentioned in the definition of BIPV (elaborated by T15-STC and published in 2018), "the BIPV is the smallest non-divisible photovoltaic unit in a BIPV system." The subdivision of the system is therefore not possible. T15 STD's decision is to include the main function AND the additional function within the framework of the comparison. This is the clearest distinction between BIPV and any other system such as BAPV or ground-mounted installations. Indeed, for BIPV, both functions are included in the product. This is not the case for BAPV which fulfils one function.

Also as reminded in the BIPV definition, BIPV cannot be subdivided into two parts representing each function, since the technical and environmental performance of the product depends on the complete integration in the BIPV system.

Following ISO 14040-44 requirements, building function and electricity production function shall be both included in the system as presented in Figure below.

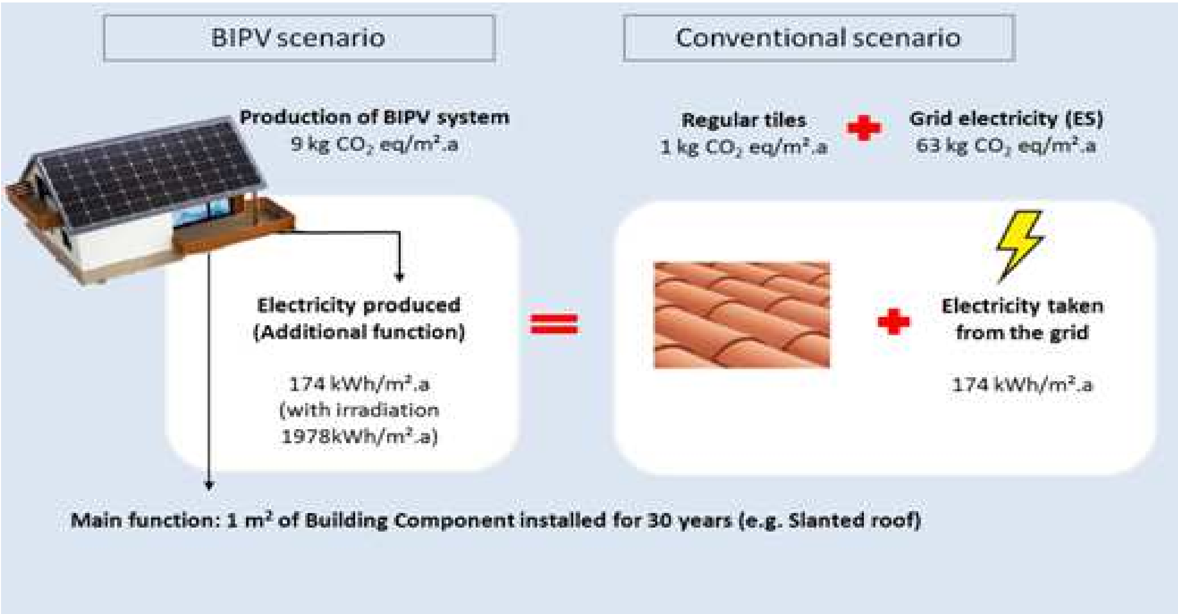

Figure 2: Managing multi-functionality using system expansion with respect to ISO 14040-44 standards. BIPV product (enabling the building function) and electricity production shall be compared with a system covering the two outputs. Therefore the carbon footprint of a BIPV system of 9 $kgCO_2eq/m^2.a$ is far lower than the regular system which is the sum of the two functions (1+63=64 $kgCO_2eq/m^2.a$). This allows a comparison between two equivalent functional systems (This illustration refers to a system installed in Spain)

Figure 2 presents (on the left part) scenario 1 which refers to the BIPV system and comprises both the building function (1 m^2 of building skin) and the electricity function (X kWh produced), and (on the right side) scenario 2, a conventional building skin with the conventional material (1 m^2 of building skin) and the electricity produced from the grid for the X kWh. Such a comparison assumes that if BIPV is not installed, electricity (used by the building or any other user) is provided by the grid.

On the same perspective, BIPV-T satisfies 3 functions, a surface of building skin, a production of electricity and a production of thermal energy. Figure 3 illustrate this situation.

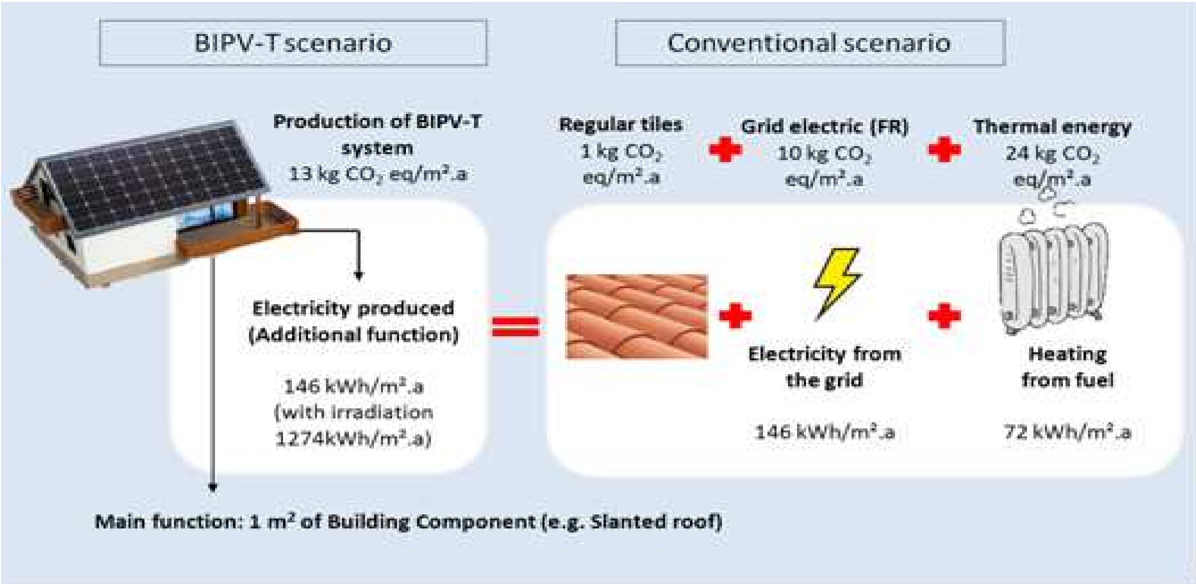

Figure 3: Managing multi-functionality using system expansion with respect to ISO 14040-44 standards. BIPV-T product enabling the building function, electricity production and thermal energy production shall be compared with a system covering the three functions separately. Therefore the carbon footprint of a BIPV system of 13 kgCO2eq/m2.a is far lower than the regular system which is the sum of the three functions (1+10+24=35 kgCO2eq/m2.a). This allows a comparison between two equivalent functional systems (This illustration refers to a system installed in France).

Systems producing both electricity and thermal energy are more and more developed since it is optimizing the surface. In that case the three functions shall be considered with respect to the ISO 14040-44 requirements.

This decision between the main function and the additional function can be discussed further since it defines the frame of the comparability for LCA. If square metre is chosen as functional unit, comparison with building skin alternatives is possible; if kWh is chosen, comparison can be made with other electricity production systems. As defined throughout the T15 STC report, BIPV fulfil two functions (a building function and an electricity production) simultaneously. The correct way to address multi-functionality, following the Life Cycle Assessment international standards ISO 14040-44 (ISO. 2006a; 2006b), is to first define the system's main function (and use it as the reference function) and then the additional function. From an LCA perspective, the main function is the one that has to be first and foremost fulfilled by the product.
For this reason, the case studies are analysed under the assumptions that the main function of the BIPV is a building function, its additional function is "producing electricity". Then the functional unit is 1 m2 of building skin covered for 30 years, producing X kWh of electricity, X being defined by the performances of the BIPV system.

4.3. Applying system extension

Resolving multi-functionality issue requires to decide the most appropriate option for the system extension. For electricity production, the system extension shall be based on an electricity network. For thermal energy production, it shall relay on the relevant energy production mean.

Concerning the system extension for electricity production, the decision made strongly affects the results of LCA.

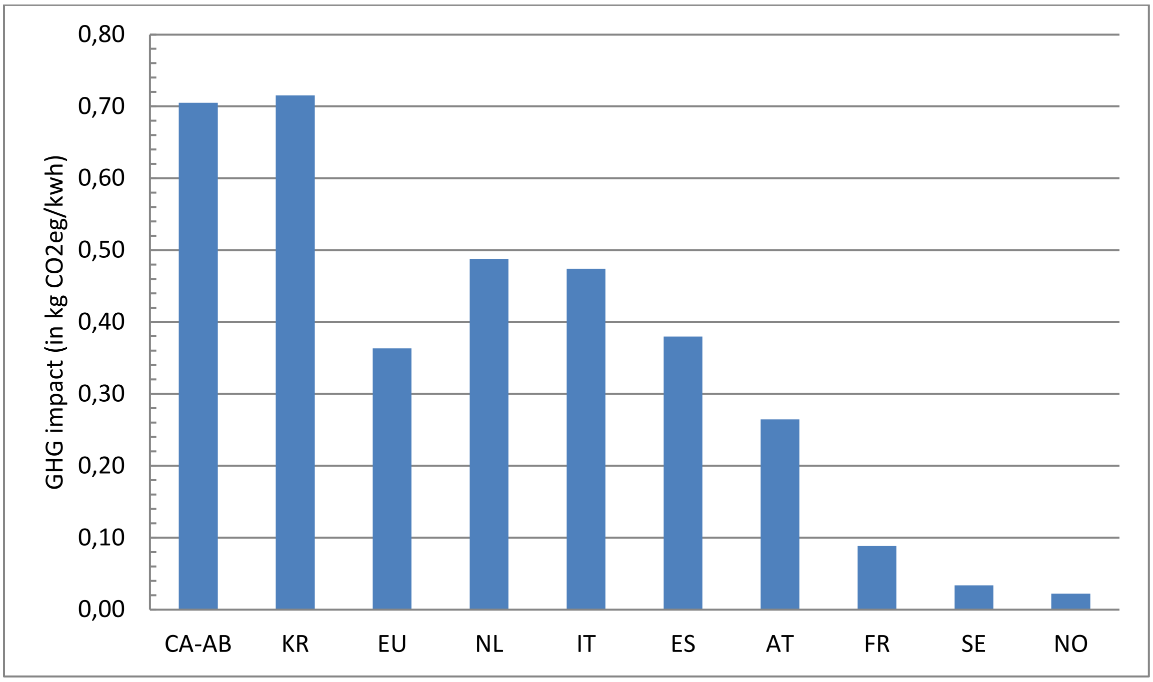

Figure 4: Comparison between the carbon footprint of the grid-mix of the 9 countries (10 grid mix including EU) involved in the project. Results range from 22 gCO_2eq/kwh (NO) to 715 gCO_2eq/kwh (KR). Data are from ENTSOE 2016 (NL, IT, ES, AT, FR, SE, NO); ecoinvent 3.5 (CA-AB) or National statistics2016 (KR).

As presented in Figure 4, the carbon footprint of the grid vary by a factor 32 (between Norway and Korea for example). Bearing in mind that a PV system typically present a carbon footprint around 80 gCO_2eq/kWh, installing BIPV can be viewed as counter-performing in Sweden or Norway for example. Nevertheless, these countries are big exporting countries to the European electricity network, which has a higher carbon footprint/kWh. Therefore depending in the system extension considered (national mix or market mix) the footprint of the system can change a lot. The choice of the grid mix considered during the use phase remains open. It shall be decided whether the relevant grid mix is the national grid mix (including production and imports) or the market grid mix (including all interconnected countries).

One shall bear in mind that any change in production means or imports is reflected by the performance of the national grid mix. Nevertheless, whether a country increases or decreases its electricity export is only reflected by the market mix and not the country mix. Therefore, for big-electricity-exporting countries, the market grid betters reflect the environmental changes due to increased capacity of renewable electricity. In the case study report, the impact assessment of each scenario was tested with country mix and market mix whenever possible.

In order to clearly presents the consequences of the decision, a detailed comparison between country mix and Market electricity mix is presented as a variant for all case studies located in Europe.

Concerning the thermal energy substitution, alternative energy source is typically a domestic energy mean (oil, gas, electricity, etc) but it can also be a heating network. This situation is addressed only in Altkirch case study (a refurbishment situation) and the calculation is based on the actual substitution of the energy in the house.

5 Case study results

Eleven different case studies are discussed in this report. They cover nine countries, three continents, three installations types, five PV technologies and different building types (residential, tertiary, etc.). Case studies' modelling are presented following three distinct sections: opaque roof BIPV (4 cases); opaque façade BIPV (5 cases) and semi-transparent façades (2 cases). Within the opaque roof scenario, only one hybrid PV and thermal module is available, it is therefore addressed in the same way as for the other opaque roofs. No semi-transparent roofs or skylights are available for testing. This category is therefore not covered. Only a limited number of technologies and BIPV solutions are addressed with the case studies, but the rules identified and the parameters selected shall be broad enough to cover most available technologies and solutions. Concomitantly, they shall be precise enough to allow decision-making when comparing BIPV with conventional materials or comparing different BIPV.

- Opaque roof category: This category is explored with 4 case studies. This BIPV solution is tested with three different technologies (multi- Si, mono-Si and BIPV-T[3] modules) in 4 different countries: Korea, Spain, France and Norway. The capacity installed ranges from 1.5 kWp to 27 kWp. The diversity of opaque roof case studies has two objectives: to identify possible specificities of different configurations of BIPV systems and cover a broad range of issues, and to validate the applicability of the tested LCA method.

- Opaque façade category: This category is assessed with 5 case studies. This BIPV solution is tested with four different technologies (mono-Si, multi-Si, a-Si and CIGS) in 5 different countries (Korea, Canada, Netherland, Sweden and Norway). The installed capacity of the façades ranked from 22 to 172 kWp. The façades tested give a good idea of the complexity of the evaluation.

- Semi-transparent façade: Only 2 case studies illustrate this category, using only mono-Si technology and both located in Europe. The main difference consists in the type of module used and the power of the system from 1.3 to 31 kWp. Nevertheless, even if the number of case studies is limited, it is a good way to test the methodology with a different category and to explore the possible limitations.

[3] BIPV-T refers to building integrated photovoltaic modules which also produce thermal energy

5.1. BIPV roof of the Public Town Building in Incheon (South Korea)

The Public Town and the JST buildings are actually two interconnected edifices built in Incheon (South Korea). PV and BIPV are installed in several places of the buildings envelope, both on façades and roofs. Modules consist of amorphous-Si or multi-Si PV. In total, more than 1 000 m^2 of PV are installed on the building, corresponding to 147.751 kWp (with 20 % PV and 80 % of BIPV). Most of the modelling is based on architects work and direct feedback from building engineers. The roof of the Public Town building has both PV and BIPV. Only BIPV is considered in the study. It is made of 197 m^2 of multi-Si PV modules integrated in the aluminium roof. Each of the 192 modules has an installed capacity of 139 Wp (total capacity is 26.688 kWp). Environmental modelling is based on data from architects' layouts and direct feedback from building engineers.

Figure 5 a and b: Public Town building (a); BIPV roof (b).

<table>
<tr><td colspan="2"><u>Functional unit</u>: 1 m^2 of building roof during 1 year.
<u>Requirements</u>: the system shall fulfil both building function and electricity production during 30 years.</td></tr>
<tr><td><u>Reference scenario</u>:
1 m^2 of Building-Integrated PV system and producing 130 kWh/a of electricity.</td><td><u>Alternative scenarios</u>:
Conventional building skin material for 1 m^2.
Electricity production corresponding to 1 m^2 of BIPV on average during one year (130 kWh) produced with the Korean grid mix for year 2016.</td></tr>
<tr><td><u>System boundaries</u>:
Modules, BOS, mounting and edging, system's end-of-life. No end-of-life recycling system extension is included.</td><td>Conventional material is considered for the building's function. Electricity produced by the grid during year 2016 (reference year) is included.</td></tr>
<tr><td><u>Technical description</u>:
The BIPV installation consists of a 197 m^2 flat roof made of multi-Si BIPV panels.
Tilt: 0 °
Module efficiency: 14 %
Installed capacity: 27 kWp
Inverters power: 30 kW
Performance ratio: 0.75
Packing factor: 0.93
Annual degradation: 0.7 %</td><td>The building skin's conventional material consists of roof aluminium plates.
Alternative: Korean's annual grid mix is used for assessing electricity production's impact on the environment.
Total irradiation received on the module plane per year: 1 479 kWh/m^2.
Total energy output over 30 years: 3 900 kWh/ m^2</td></tr>
<tr><td colspan="2"><u>Data sources</u>: Irradiation data are provided by the building engineer. Activity data stem from the architects' documentation. All background data originate from ecoinvent 3.5.</td></tr>
</table>

Impact assessment:

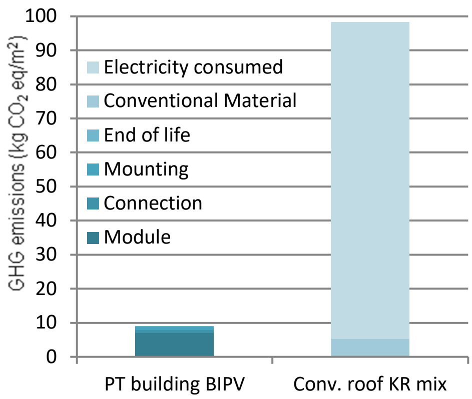

Figure 6: Comparison of the GHG emissions of the roof BIPV system per m² during one year with the alternative scenarios where electricity is produced by the Korean mix.

The carbon footprint of the BIPV system is dominated by the module with 79 % of the impacts, while mounting accounts for 11 % and electric connections to the grid (inverters, cables, etc.) 9 %. The BIPV system's end-of-life is negligible but only includes collection and sorting. No recycled material is accounted as a benefit at end-of-life since we consider a steady state system with an identical recycled material input/output. Aluminium plates have a high impact (5.2 $kgCO_2eq/m^2.a$). For electricity production, the alternative scenario with a Korean mix points out that BIPV installations are very efficient in terms of environmental performance (carbon emissions reduction). This is explained by the high carbon footprint of the Korean electricity mix (715 gCO_2eq/kWh), while the multi-Si modules are rather efficient.

Interpretation:

The results are partly based on assumptions. Modelling of modules, inverters, mounting system and conventional materials' environmental impacts are based on generic life cycle inventories. Module irradiation is estimated by building engineer with monthly data. KWh's carbon footprint is also assessed on a monthly basis to avoid any bias during the environmental assessment. Both performance ratio and degradation factors are based on default values commonly used in scientific articles. The performance ratio particularly needs further investigation. Indeed, dust, soiling, atmospheric pollution, potential inverter breakdown or cabling issues (for example) are not considered and can lead to a reduced performance ratio. It is interesting to see that the BIPV can compete with the alternative conventional material in terms of environmental performance (per m² of building skin covered), even without producing electricity. This needs to be confirmed with specific data, especially for modules, mounting system and aluminium plates. This only partly explains the very good performance of BIPV. The reason is mainly due to kWh's high carbon footprint in Korea (close to 715 gCO_2eq/kWh). The carbon payback time is less than 3 years, showing that installing BIPV systems in Korea is of great environmental interest.

Conclusions:

The Public Town building project is well documented but since it is a new building, all the data pertaining to the efficiency of the system are based on assumptions. The system's environmental assessment is still very promising, the carbon footprint per square metre of BIPV is rather small and the conventional material presents a high footprint. It is one of the rare cases which is favourable, even at-the-material level. In addition, Korea's conventional energy source has a high carbon footprint, which makes the system even more efficient in terms of environmental footprint.

5.2. BIPV roof of the Zaragoza House in Spain

The Zaragoza house, located in Spain, is an entirely virtual house described in a scientific article (Zabalza Bribian et al, 2009). It is presented as a two-floor 222 m² house located in Zaragoza. The house is presented in detail in the publication. Electricity is assumed to stem from a BIPV system integrated on a slanted south-facing roof. The BIPV system is composed of 20 m² of multi-Si PV. The house is purely used as a support for integrating BIPV during case study modelling. While conventional case studies are based on existing or future buildings, this case study aims at demonstrating that only orientation and tilt are needed to model the environmental performances of BIPV. Representative values (for a given country), orientation and tilt (defined according to the BIPV solution) (e.g. façade, slanted roof, flat roof…) enable the assessment of the BIPV environmental footprint.

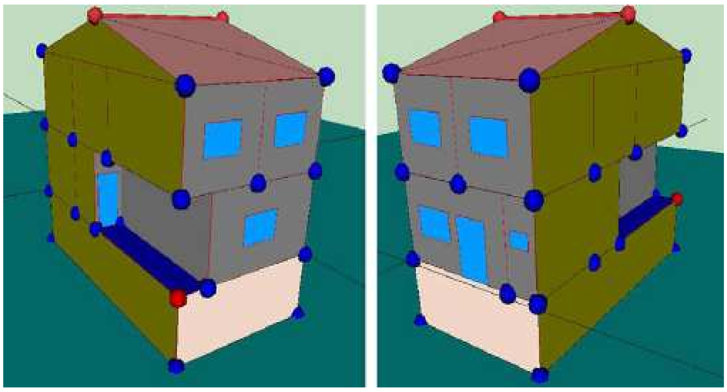

Figure 7: Zaragoza house model (Zabalza Bribián, Aranda Usón, et Scarpellini 2009)

<table>
<tr><td colspan="2"><u>Functional unit</u>: 1 m² of building skin during 1 year.
<u>Requirements</u>: the system shall fulfil both building protection and electricity production during 30 years.</td></tr>
<tr><td><u>Reference scenario</u>:
1 m² of Building-Integrated PV system producing 174 kWh of electricity in average every year.</td><td><u>Alternative scenarios</u>:
Conventional building skin material for 1 m². Electricity production corresponding to 1 m² of BIPV on average during one year (174 kWh) produced with the Spanish or European grid mix for year 2016 using ENTSOE data.</td></tr>
<tr><td><u>System boundaries</u>:
Modules, BOS, mounting and edging, system’s end-of-life. No potential recycling system extension is included.</td><td>Conventional material is considered for the building’s function. Electricity produced by the grid in 2016 (reference year) is included.</td></tr>
<tr><td><u>Technical description</u>:
The BIPV installation consists of 20 m² of multi-Si PV modules facing south, integrated into a roof tile.
Tilt: 30 °
Module efficiency: 14 %
Installed capacity: 3 kWp
Inverters power: 2.5 kW
Performance ratio: 0.75
Packing factor: 0.93
Annual PV degradation: 0.7 %/a</td><td>The building skin’s conventional material is a typical roof tile.
Alternative (a): the country’s monthly grid mix (Spain) (including imports) is used for assessing electricity production’s impact on the environment.
Alternative (b): the monthly market mix (Europe) is used for assessing electricity production’s impact on the environment.
Yearly in plane irradiation per m² of module: 1 978 kWh/m² (based on monthly estimates).
Total electricity output over 30 years: 5 213 kWh/m² (based on monthly calculations).</td></tr>
</table>

Data sources: monthly irradiation data are estimated using the PVGIS software (JRC, Ispra). Activity data are collected from the Zaragoza house publication. All background data are from ecoinvent 3.5.

Impact assessment:

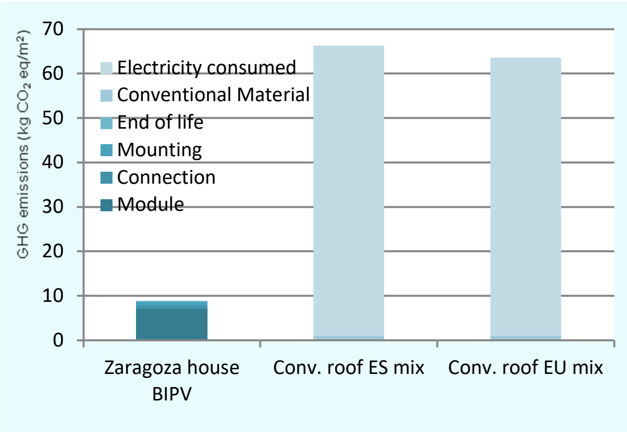

Figure 8: Comparison of GHG emissions of the BIPV system per m^2 during one year with the conventional scenarios; alternative 1: electricity is produced by the Spanish mix; alternative 2: electricity is produced by the European mix.

Carbon footprint is similar between the Spanish and the European electricity mix. In both cases, the BIPV system presents a significant improvement. The BIPV system's carbon footprint is dominated by the module with 80 % of the impacts, while mounting and flashing account for 10 % and connections to the grid (inverters, cables, etc.) 8 %. The BIPV systems' end-of-life is negligible but only includes collection and sorting. No recycled material is accounted as a benefit at end-of-life since we consider a steady state system with the same input and output of recycled material. Compared to the carbon footprint of the production of the BIPV system, the roof tile has 8 times less impacts.

Interpretation:

Modelling is partly based on assumptions. Modules, inverters, mounting system and tiles' environmental impacts are based on generic life cycle inventories. Irradiation data are based on monthly estimates using the PVGIS software (JRC, Ispra). Energy production data are calculated on a monthly basis so as to avoid any bias during electricity footprint's calculation, when comparing scenarios. Indeed, PV production is higher (during the summer) when kWh's footprint is lower. Monthly data, both for PV electricity production and electricity mix, avoids an overestimation of the environmental benefits. The performance ratio is 0.75 (a value commonly used for rooftops). The degradation factor of 0.7 % per year is based on default values commonly used in scientific articles. The lifetime of the PV (≈ 30 years) complies with existing guidelines. However, architects and building engineers usually consider that building component or even the building lifetime shall be considered. It assumes that the PV system is not replaced, provided that the building's function is fulfilled. Equivalent PV and building life spans would reduce BIPV impacts by 50 %. The system's carbon payback time (CPBT) is approximately 4 years, both with the Spanish and the European electricity mix. Comparing environmental performance results between Europe and Spain provides extremely close figures. This is due to both countries' mixes' very similar carbon footprint per kWh: 380 gCO_2/kWh for Spain and 360 gCO_2/kWh for Europe.

Conclusions:

The Zaragoza case study demonstrates that it is possible to assess the environmental footprint of BIPV systems, even with an entirely theoretical situation. For this case study, we went through scientific publications for framing the assessment. But building a consensus on the type of default data (that can be used per country) would allow to conduct an LCA with validated assumptions in a comparative framework.

5.3. BIPV roof of the Altkirch House in France

The Altkirch house is a residential single-family house located in France. A 10 m^2 Building-Integrated thermal and photovoltaic system is replacing part of the external roofing material. The system was installed in 2013 and fulfils three functions: building protection (as part of the building skin), renewable electricity generation and thermal energy production. The system consists of 6 BIPV-T modules. Thermal energy production has two purposes: first, increase the module's overall energy efficiency; second, cool down the PV module and increase the amount of electricity produced. A complete monitoring system records module temperature, heated water and electricity output. These data are used for modelling the house's environmental performance.

Figure 9: a and b: Altkirch house (a); Integration of the BIPV-T panels (b) (Dualsun, 2019).

Functional unit: 1 m^2 of building skin during 1 year. Requirements: the system shall fulfil building protection, electricity generation and hot water production during 30 years.	
Reference scenario: 1 m^2 of Building-Integrated BIPV-T system producing 146 kWh of electricity and 72 kWh of water heating.	Alternative scenarios: Conventional building skin material for 1 m^2. Thermal energy production corresponding to 1 m^2 of BIPV on average during 1 year (72 kWh) assuming heating is produced with fuel. Electricity production corresponding to 1 m^2 of BIPV on average during one year (146 kWh) produced with the French or European grid mix for year 2016 (using ENTSOE data).
System boundaries: Modules, BOS, mounting and edging, system's end-of-life. No potential recycling system extension is included.	Conventional material is considered for the building's function. Electricity produced by the grid during year 2016 (reference year) is included.
Technical description: The BIPV installation consists of 10 m^2 of mono-Si PV-T panels facing south, integrated into a roof tile. Tilt: 40 ° Module efficiency: 15.4 % Installed capacity: 1.5 kWp Inverters power: 1.5 kW Performance ratio: N.R. Packing factor: 0.88 Annual PV degradation: 0.7 %	The building skin's conventional material is a standard roof tile. Alternative (a): the country's monthly grid mix (France) (including imports) is used for assessing electricity production's impact on the environment. Alternative (b): the monthly market mix (Europe) is used for assessing electricity production's impact on the environment. Total electric energy output over 30 years: 4 391 kWh/m^2. Total thermal energy output over 30 years: 2 160 kWh/m^2.

Data sources: BIPV's thermal and electric output stem from the monitoring system (considering an average year). Activity data used for modelling the PV-T panels and the system is provided by Dualsun and based on site measures. Background data originates from ecoinvent 3.5.

Impact assessment:

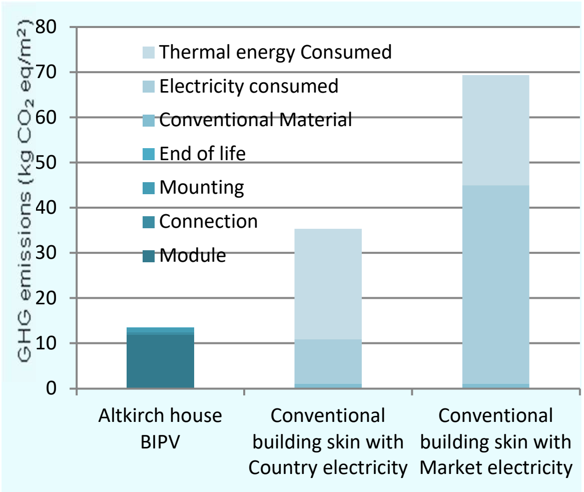

Figure 10: Comparison of the GHG emissions of the BIPV system per m2 during one year with the conventional scenarios; alternative 1: electricity is produced by the French mix; alternative 2: electricity is produced by the European mix. In both cases, thermal energy (in the conventional scenario) is produced with fuel.

The comparison shows that BIPV-T modules enable to reduce the footprint of the building skin. The BIPV-T system's carbon footprint is dominated by the module with 88 % of the impacts, while mounting and flashing account for 6 % and electric connections to the grid (inverters, cables, etc.) 5 %. The BIPV system's end-of-life is negligible but only includes collection and sorting. No recycled material is accounted as a benefit at end-of-life since we consider a steady state system with an identical recycled material input/output. Compared to the BIPV-T system, the roof tile has 13 times less GHG emissions. For electricity production, the alternative scenario with a French mix points out that BIPV installations worsen the carbon footprint but are still favourable due to their thermal energy production ability. With a European electricity mix, BIPV-T systems are favourable both for their electricity generation and thermal energy production ability. The alternative thermal energy production system is assumed to be fuel heating since it corresponds to the previous installation.

Interpretation:

Modelling is partly based on assumptions. Modules, inverters, mounting system and tiles' environmental impact are based on generic life cycle inventories. The module's thermal and electric production is monitored. Energy production data is reported on a monthly basis so as to avoid any bias in electricity footprint's calculation with the alternative scenario. Indeed, PV production is higher (during the summer) when kWh's footprint is lower. Monthly calculations avoid an overestimation of the environmental benefits. Degradation factors are based on default values commonly used in scientific articles.

The comparison with a conventional solution based on a French electricity mix is not in favour of BIPV-T installations; only the fuel saved thanks to thermal production makes BIPV-T better. Indeed, PV-T module production is impactful. Still, the choice of the French mix as the alternative electricity mix is disputable: country mixes consider electricity production and importation but do not take into account exportation. For net-exporter-of-electricity countries like France, the environmental improvement of the market grid mix (thanks to an increase in renewable electricity production capacity) is not reflected by the country mix. The most relevant indicator of the environmental performance of the BIPV alternative scenario is market electricity mix (also called European grid mix). It is also reflected by the system's carbon payback time (CPBT): the system's CPBT is 12 years if a French mix is considered. It decreases to 6 years with a European mix. An electric-production-only (9 years CPBT) simulation shows that the hybrid module (delivering both electricity and hot water) presents highly enhanced environmental performances.

Conclusions:

The Altkirch case study demonstrates that the approach developed in the project is also compatible with hybrid PV systems. It also shows that hybrid PV systems can significantly reduce BIPV's carbon footprint.

5.4. BIPV roof of the Living Lab building in Norway

The Living Lab is a one-storey residential building designed within the framework of the Norwegian Zero Emission Buildings pilot studies. It was constructed in Trondheim (Norway) in 2015. Most of the data are from Zeb project's report no.24 (Inman et Houlihan Wiberg 2015), but several publications describing the building were also used for the assessment of the BIPV system (Goia, Finocchiaro, et Gustavsen 2015; Good et al. 2014; Finocchiaro et al. 2014; Kristjansdottir et al. 2016; Korsnes 2017).

Figure 11: a and b: Living Lab building (a); Integration of the PV panels (b) (Inman et Houlihan Wiberg 2015).

Functional unit: 1 m^2 of building skin during 1 year. Requirements: the system shall fulfil both building protection and electricity production during 30 years.	
Reference scenario: 1 m^2 of Building-Integrated PV system producing 118 kWh.	Alternative scenarios: Conventional building skin material for 1 m^2. Electricity production corresponding to 1 m^2 of BIPV on average during one year (118 kWh) produced with the Norwegian or European grid mix for year 2016 (using ENTSOE data).
System boundaries: Modules, BOS, mounting and edging, system's end-of-life. No potential recycling system extension is included.	Conventional material is considered for the building's function. Electricity produced by the grid in 2016 (reference year) is included.
Technical description: The BIPV installation consists in an area of 79.2 m^2 of multi-Si PV panels facing south integrated in a bitumen roof. Tilt: 30 ° Module efficiency: 15.8 % Installed capacity: 12.5 kWp Inverters power: 9.2 kW Performance ratio: 0.75 Packing factor: 0.93 Annual efficiency degradation: 0.7 %	The building skin's conventional material is a standard bitumen for roofs. Alternative (1): the country's monthly grid mix (including imports) is used for assessing electricity production's impact. Alternative (2): the monthly market mix is used for assessing electricity production' impact. Total irradiation received on the module plane per year: 1 193 kWh/m^2. Total energy output over 30 years: 3 551 kWh/m^2.
Data sources: irradiation data are estimated using the PVGIS software (JRC, Ispra). Activity data are collected from the Living Lab's publications. All background data originate from ecoinvent 3.5.	

Impact assessment:

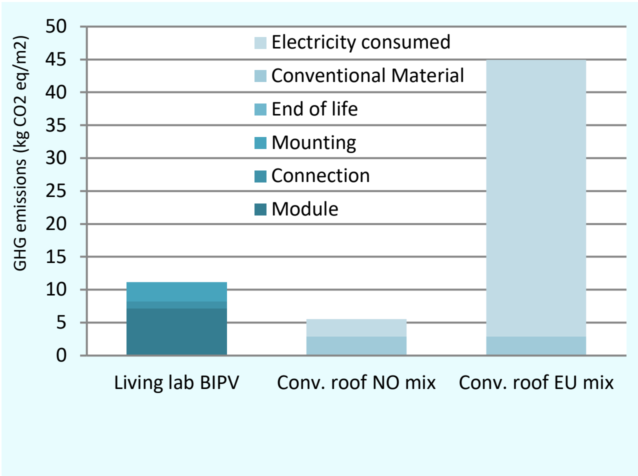

Figure 12: Comparison of the GHG emissions of the BIPV system per m² during one year with the conventional scenarios; alternative 1: electricity is produced by the Norwegian mix; alternative 2: electricity is produced by the European mix.

The BIPV system's carbon footprint is dominated by the module with nearly 2/3rds of the impacts, while mechanical links with the roof (mounting and edging) account for 25 % and electric connections to the grid (inverters, cables, etc.) 10 %. The BIPV system's end-of-life is negligible but only includes collection and sorting. No recycled material is accounted as a benefit at end-of-life since we consider a steady state system with an identical input/output of recycled material. Compared to the BIPV-system-equipped roof, the bitumen roof (conventional material) presents 25 % of impacts. For electricity production, the alternative scenario with the Norwegian mix points out that the BIPV installation worsens carbon emissions, while it is very beneficial when compared to the EU mix.

Interpretation:

The results are partly based on assumptions. Modules, inverters, mounting system and bitumen's environmental impacts are based on generic life cycle inventories. The module's irradiation is based on estimations originating from the PVGIS software, but monthly irradiation data are used so as to avoid an overestimation of BIPV's environmental benefits. Both performance ratio and degradation factors are based on default values commonly used in scientific articles. The comparison with a conventional solution based on the Norwegian mix is not in favour of BIPV installations. But Norwegian mix's modelling include produced and imported electricity but no electricity exports. Indeed, exported electricity can be used by any country as part of the electricity market. Therefore, for a net-exporter-electricity country, an increase in its renewable electricity production capacity affects the market mix and that is not being reflected by the country mix. For Norway, the European (market) electricity mix better reflects the environmental grid evolution owing to the installation of BIPV.

Conclusions:

The Living Lab is a very detailed and complete case study. The level of detail for material allows us to assess accurately the BIPV system. The results also show that, in terms of carbon footprint, Norwegian BIPV installations should be motivated by the export of renewable electricity into the EU market. Indeed, only export makes BIPV installations environmentally favourable in Norway compared to the national electricity network.

5.5. BIPV façade of the JST building in Incheon (South Korea)

The JST and the Public Town buildings are actually two interconnected edifices located in Incheon, South Korea. PV and BIPV are installed in several places of the building(s), both on façades and roofs. Modules can be amorphous Si PV or multi Si PV. In total, more than 1 000 m^2 of PV is installed on the building(s), corresponding to 147.751 kWp, with a total of nearly 80 % of BIPV. Most of the modelling is based on architect work and direct feedback from building engineers. The façade assessed during the case study includes the (a-Si) western and south façade of the (JST) building, fully PV-integrated and covering a surface of 212 m^2. a-Si BIPV modules (transparency 20%) installed in the southern façade. They are two kinds size related with near glass size. Its power is 94 Wp and 70 Wp each (total capacity is 10.128 kWp). a-Si opaque modules are installed in the western façade on aluminium sheets. It is composed of 88 modules of 115 Wp (total capacity is 10.12 kWp).

Figure 13: a and b: JST building (a); East façade BIPV (b).

<table>
<tr><td colspan="2"><u>Functional unit</u>: 1 m^2 of building façade during 1 year.
<u>Requirements</u>: the system shall fulfil both building function and electricity production for 30 years.</td></tr>
<tr><td><u>Reference scenario</u>:
1 m^2 of Building-Integrated PV system tested in 2 situations and producing every year 42 kWh/m^2 on the west façade and 56 kWh/m^{2}on the south one.</td><td><u>Alternative scenarios</u>:
Conventional building skin material for 1 m^2. Electricity production corresponding to 1 m^2 of BIPV on average during one year (50 kWh) produced with the with Korean grid mix for year 2016.</td></tr>
<tr><td><u>System boundaries</u>:
Modules, BOS, mounting and edging, system’s end-of-life. No end-of-life recycling system extension included.</td><td>Conventional material is considered for the building’s function. Electricity produced by the grid for year 2016 (reference year) is included.</td></tr>
<tr><td><u>Technical description</u>:
Installed BIPV consist in an area of 90 m^2 of west oriented façade and 122 m^2 of south oriented façade made of a-Si panels.
Tilt: 90 °
Module efficiency: 7,6 %
Installed capacity: 20 kWp
Inverters power: 25 kW
Performance ratio: 0.75
Packing factor: 0.97
Annual degradation: 0.7 %</td><td>The building skin’s conventional material is a aluminium-or a glass cladding façade.
Alternative: the annual Korean grid mix is used for assessing electricity production’s impact.
Total irradiation received on the module plane per year: 840 kWh/m^2 (west) and 1122 kWh/m^2 (south).
Total energy output over 30 years: 2929 kWh/m^2.</td></tr>
<tr><td colspan="2"><u>Data sources</u>: irradiation data are provided by the building’s engineer. Activity data are collected from the architect’s documentation. All background data are from ecoinvent 3.5.</td></tr>
</table>

Impact assessment:

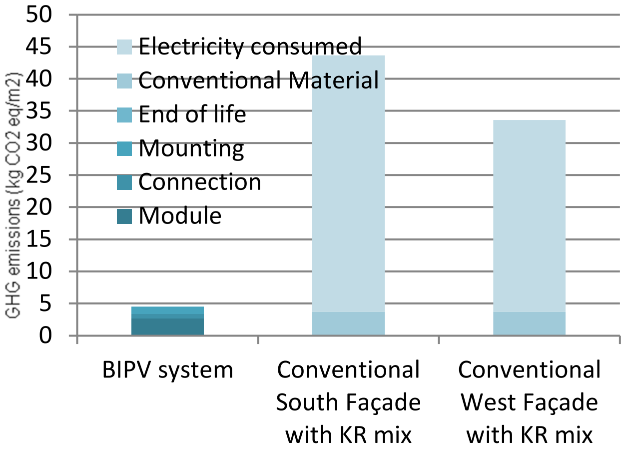

Figure 14: Comparison of the GHG emissions of the BIPV system per m² during one year with the alternative scenarios where electricity is produced by the Korean mix for the south façade (more electricity needed) or the east façade (less electricity needed).

The BIPV system's carbon footprint is dominated by the module with 60 % of the impacts, while mounting accounts for 25 % and electric connections to the grid (inverters, cables, etc.) 14 %. The BIPV system's end-of-life is very small but only includes collection and sorting. No recycled material is accounted as a benefit at end-of-life since we consider a steady state system (identical recycled material input and output). Compared to the BIPV-system-equipped façade, the glass façade features a 82 % impact rate. For electricity production, the alternative scenario with a Korean mix points out that the BIPV installation is very efficient in terms of environmental performances (carbon emissions reduction).

Interpretation:

The results are partly based on assumptions. Modules, inverters, mounting system and conventional material environmental impacts are based on generic life cycle inventories. Module irradiation is estimated by the building's engineer. Both performance ratio and degradation factors are based on default values commonly used in scientific articles. The performance ratio particularly needs further investigation since it is sometimes questioned by scientists, especially as for façade systems are concerned. Indeed, dust, soiling, atmospheric pollution, potential inverter breakdown or cabling issues (for example) are not considered and can lead to a reduced performance ratio. Still, the comparison with a free-PV building and energy system is strongly in favour of BIPV (due to the kWh high carbon footprint in Korea: 715 gCO_2eq/kWh). The environmental payback time ranges between 3,5 and 5 years both for the southern and the eastern façade.

Conclusions:

The JST building is covered with BIPV on several façades and on the roof. Monitored data are not available, but BIPV have a high efficiency, which allows significant electricity generation. Considering Korea's electricity mix carbon footprint, the carbon footprint of the BIPV system is environmentally-friendly. Nevertheless, it would be interesting to have monitored data which confirm electricity prediction overtime.

5.6. BIPV façade of the Jeanne and Peter Lougheed Arts Centre in Camrose (Canada)

The Jeanne & Peter Lougheed Arts Centre is located on the University of Alberta's Augustana Campus in Camrose, Alberta. This 550-seat theatre features some of the best solutions in terms of energy-efficiency measures and renewable energy production. BIPV is used as cladding for the building four façades and covers more than 850 m^2. Most of the data are from articles, reports and technical datasheets (Howell 2015; 2016; Conergy 2012).

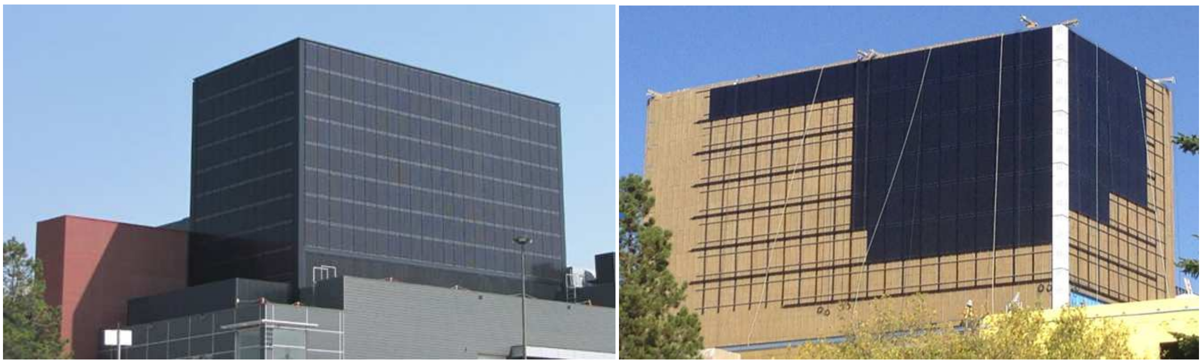

Figure 15: a and b: Arts Centre building (a); Integration of PV modules as BIPV cladding (b). (Photo credit: Gordon Howell).

Functional unit: 1 m^2 of building façade during 1 year. Requirements: the system shall satisfy both building function and electricity production for 30 years.	
Reference scenario: 1 m^2 of Building-Integrated PV system producing 135 kWh/a on the south façade, or 98 kWh/a on the east and west façades, or 53 kWh/a on the north façade (4 cases tested: south, east, west, north).	Alternative scenarios: Conventional building skin material for 1 m^2. Electricity production corresponding to 1 m^2 of BIPV on average during one year (135 kWh south façade, 98 east and west façades; 53 north façade) produced with Alberta's grid mix for the year 2016.
System boundaries: Modules, BOS, mounting and edging, end-of-life of the system. No system extension for recycling is included.	Conventional material is considered for the building's function. Electricity produced by the grid in 2016 (reference year) is included.
Technical description: The BIPV system installed consists of a 867 m^2 cladding façade with 137 m^2 facing south, 341 m^2 facing west, 213 m^2 facing east and 176 m^2 facing north. The cladding façade consists of mono-Si PV modules. Tilt: 90 ° Module efficiency: 15.2 % Installed capacity: 122 kWp Inverters power: 122 kW Performance ratio: 0.75 Packing factor: 0.93 Annual degradation rate: 0.7 %	The conventional material for the building's skin is an aluminium cladding façade. Alternative: Alberta's annual grid mix is used for assessing the impacts of electricity production. Total irradiation received on the module plane per year is 1 415 kWh/m^2 south façade, 1 028 kWh/m^2 west and east façades, 557 kWh/m^2 north façade. Total energy output over 30 years: 11 529 kWh/m^2 (4 050, 2 093 and 1 593 respectively).
Data sources: irradiation data are provided by the building's designer. Activity data are collected from publications. All background data originate from ecoinvent 3.5.	

Impact assessment:

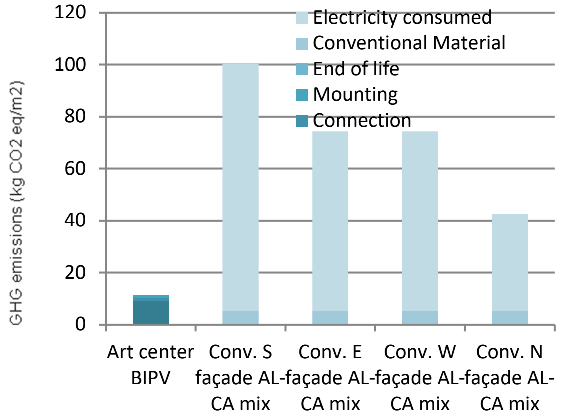

Figure 16: Comparison of GHG emissions of the BIPV system per m² during one year with the alternative scenario where electricity is produced by the Alberta mix.

The carbon footprint of the BIPV system is dominated by the module with more than 80 % of the impacts, while mounting and electric connections to the grid (inverters, cable, etc.) represent 10 % and 8 % respectively. The BIPV system's end-of-life is negligible but only includes collection and sorting. No recycled material is taken into account as a benefit at end-of-life for the reason that we consider a steady state system (identical input and output of recycled material). The aluminium cladding façade has 45 % more GHG emissions than the BIPV system. For electricity production, Alberta's mix alternative scenario points out that BIPV installations always tend to lower carbon emissions.

Interpretation:

Results are partly based on assumptions. Modules, inverters, mounting system and aluminium plates' environmental impacts are based on generic life cycle inventories. Module irradiation is quantified by the BIPV system's designer, but only annual irradiation is provided. This nurtures environmental benefits' overestimation (assuming an equal summer/winter distribution of the sun, as well as a constant kWh footprint over the year). Both performance ratio and degradation factors are based on default values commonly used in scientific articles. The performance ratio particularly needs further investigation since it is based on empirical estimate and sometime questioned by scientists, especially for façade systems. Indeed, dust, soiling, ice, potential inverters breakdown and cabling issues (for example) are not considered and can lead to reduced performance ratios. Still, the comparison with a PV-free building and electricity grid is strongly in favour of BIPV (i.e. high kWh carbon footprint in Alberta: (approximately 705 gCO_2eq/kWh). The environmental payback time seems to be good even for the northern façade (CPBT= 8.5 years) and even better for the southern façade (approximately 3.5 years). PV's generic life cycle inventories derive from ecoinvent assumptions, specific data for modelling the BIPV system could lead to slightly different results.

Conclusions:

The Camrose building is a very good example of façade-integrated PV systems. The area on all the façades of the building shows that, even with a northern orientation, BIPV are still environmentally favourable. Still, electricity production is based on irradiation estimates and monitored data is strongly needed validate the results.

5.7. BIPV façade of De Willem de Zwijger buildings in Best (the Netherlands)

The De Willem en de Zwijger buildings are two refurbished buildings located in Best in the Netherland. The two parallel buildings are renovated with BIPV façades (three façades per building). In total, 1 151 CIGS modules are installed for a total surface of 1 250 m^2 and an installed capacity of 172 kWp. Most of the data derive from architect layouts and project information. The opaque façades assessed during the study face south-east for the main façade where BIPV are placed both on the balconies and the walls. The secondary PV-equipped façades face south-west and north-east. Façades' surfaces are respectively 668 m^2, 292 m^2 and 290 m^2.

Figure 17: a and b: De Willem de Zwijger buildings (a); BIPV mounting system (b).

<table>
<tr><td colspan="2"><u>Functional unit</u>: 1 m^2 of building façade during 1 year.
<u>Requirements</u>: the system shall satisfy both building function and electricity production for 30 years.</td></tr>
<tr><td><u>Reference scenario</u>:
1 m^2 of Building-Integrated PV system with three orientations and an electricity production of 76 kWh for the south-east façade, 72 kWh for the south-west façade and 40 kWh for the North east.</td><td><u>Alternative scenarios</u>:
Conventional building skin material for 1 m^2. Electricity production corresponding to 1 m^2 of BIPV during one year (76 kWh SE, 72 kWh SW and 40 kWh NE façade) produced with the with Dutch or European grid mix for year 2016 using ENTSOE data.</td></tr>
<tr><td><u>System boundaries</u>:
Modules, BOS, mounting and edging, system's end-of-life. No end-of-life recycling system extension is included.</td><td>Conventional material is considered for the building's function. Electricity produced by the grid in 2016 (reference year) is included.</td></tr>
<tr><td><u>Technical description</u>:
Installed BIPV consist in a 1 250 m^2 cladding façade facing south-east (668 m^2), south-west (292 m^2) and north-east (290 m^2). Façades are equipped with CIGS panels.
Tilt: 90 °
Module efficiency: 13.8 %
Installed capacity: 172 kWp
Inverters power: N/A
Performance ratio: 0.75
Packing factor: 0.97
Annual degradation: 0.7 %</td><td>The building skin's conventional material is an aluminium cladding façade.
Alternative (a): the monthly Dutch grid mix (including imports) is used for assessing electricity production's impact.
Alternative (b): the monthly market (European) mix is used for assessing electricity production's impact.
Total irradiation received on the module plane per year is : 804 kWh/m^2 (SW), 841 kWh/m^2 (SE), 440 kWh/m^2 (NE).
Total energy output over 30 years: 5 653 kWh/m^2 (SE: 2 280, SW: 2 180, NE: 1 193 kWh/m^2).</td></tr>
<tr><td colspan="2"><u>Data sources</u>: irradiation data are assessed using the PVGIS software. Activity data are from the architects layouts. All background data originate from ecoinvent 3.5.</td></tr>
</table>

Impact assessment:

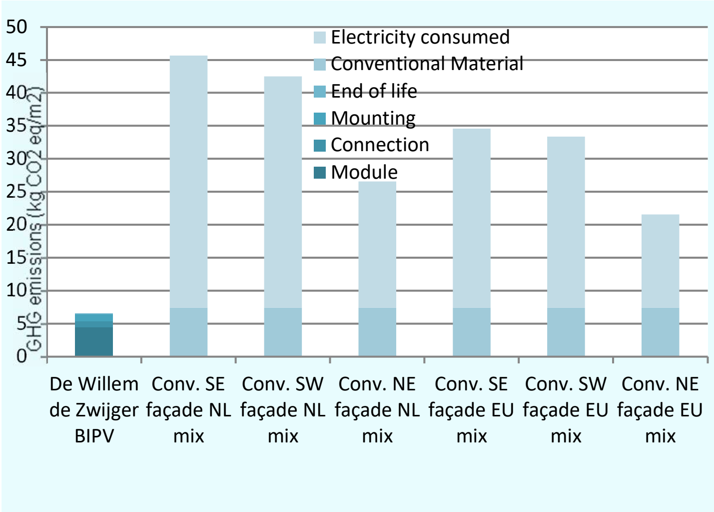

Figure 18: Comparison of the BIPV system's impact on climate change per m^2 during one year with the alternative scenarios where electricity is produced with the Dutch mix as for the south-east (SE), south-west (SW) and north-east (NE) façades. Dutch electricity mix (NL) and European electricity mix (EU) are explored in the comparison.

The BIPV system's carbon footprint is dominated by the module with 68 % of the impacts, while mounting accounts for 17 % and electric connections to the grid (inverters, cables, etc.) 13 %. The BIPV system's end-of-life makes up approximately 1 % (collection and sorting only included). No recycled material is accounted as a benefit at end-of-life for the reason that we consider a steady state system (identical recycled material input and output). BIPV-system-equipped façades and aluminium façades show similar impacts, mainly due to a bigger rigidity-driven structure as for the latter is concerned. For electricity production, the alternative scenario with the Dutch mix points out that BIPV installations are very efficient in terms of environmental performance (carbon emissions reduction). This is mainly due to Netherlands' kWh carbon footprint (nearly 480 g/kWh, while EU's carbon footprint is in the region of 360 g/kWh).

Interpretation:

Results are partly based on assumptions. Modules, inverters, mounting system and conventional materials' environmental impacts are based on generic life cycle inventories. Monthly module irradiation is estimated using the PVGIS software. KWh carbon footprint is also assessed on a monthly basis so as to avoid any bias. Both performance ratio and degradation factors are based on default values commonly used in scientific articles. The performance ratio particularly needs further investigation since it is the only available piece of data which is, however, sometimes questioned by scientists, especially as for façade systems are concerned. Indeed, dust, soiling shadow, potential inverter breakdown or cabling issues (for example) are not considered and can lead to reduced performance ratios. More accurate performance ratios should be calculated since existing publications suggest that they sometimes decrease for BIPV façades reaching sometime 0.6. Still, the comparison with a free-PV building and energy system is strongly in favour of BIPV, even with CIGS-like thin film PV. PV production generates less impacts and PV efficiency is rather high. Therefore the CPBT (Carbon Payback Time) ranges between 5 and 10 years with a Dutch mix and vary between 7 and 14 years with a European grid mix.

Conclusions:

Building installation data are very detailed and both buildings host very large surfaces of BIPV. In addition, the CIGS technology features both a very good efficiency and a rather low footprint. Monitored data over time would help environmental modelling, especially for recalculating performance ratio on actual data. The results show that BIPV systems are profitable on all façades, both with a country mix and a market mix. However, the Netherlands not being an electricity net exporter, a country mix can be a good estimate of the impact.

5.8. BIPV façade of the Frodeparken building in Uppsala (Sweden)

The Frodeparken building is newly constructed with a BIPV façade. The building is located near the train station at the entrance of the city of Uppsala (Sweden). It is a multifamily residential building. The curved-shape ventilated BIPV façade, mainly facing south, is made of 1 181 modules covering an area of 900 m^2. The system's installed capacity is equal to 100 kWp. Most of the data derives from a LCA study conducted in 2015 (Lundgreen 2015). Additional data were provided directly by White Arkitekter.

Figure 19: Frodeparken building (a); Details of BIPV (b).

<u>Functional unit</u>: 1 m^2 of building façade during 1 year. <u>Requirements</u>: the system shall satisfy both building function and electricity production for 30 years.	
<u>Reference scenario</u>: 1 m^2 of Building-Integrated PV system producing 61 kWh of electricity.	<u>Alternative scenarios</u>: Conventional building skin material for 1 m^2. Electricity production corresponding to 1 m^2 of BIPV on average during one year (61 kWh) produced with the Swedish or European grid mix for year 2016 using ENTSOE data.
<u>System boundaries</u>: Modules, BOS, mounting and edging, system's end-of-life. No end-of-life recycling system extension included.	Conventional material is considered for the building's function. Electricity produced by the grid for year 2016 (reference year) is included.
<u>Technical description</u>: Installed BIPV consist in a 900 m^2 curved-shape façade cladding facing south made of CIGS panels. Tilt: 90 ° Module efficiency: 11.8 % Installed capacity: 100 kWp Inverters power: 84 kW Performance ratio: 0.75 Packing factor: 0.97 Annual degradation: 0.7 %	The building skin's conventional material is a cement-tile façade. Alternative (a): the monthly Swedish grid mix (including imports) is used for assessing electricity production's impacts. Alternative (b): the monthly market mix (European) is used for assessing electricity production's impacts. Total irradiation received on the module plane per year: 886 kWh/m^2. Total energy output over 30 years: 2055 kWh/m^2
<u>Data sources</u>: irradiation data are assessed using the PVGIS software (JRC, Ispra). Activity data are from the architect's layouts. All background data are from ecoinvent 3.5. Data provided by Building engineer and measured on the building are higher but it is not considering future shading due to constructions in the neighbourhood which will bring overall irradiation close to the value considered here.	

Impact assessment:

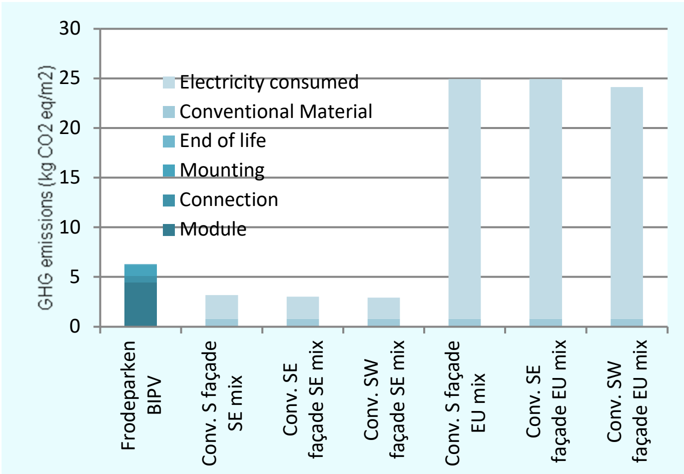

Figure 20: Comparison of GHG emission of the BIPV system per m² during one year with the alternative scenarios where electricity is produced by the Swedish mix in the Frodeparken façade. In order to better reflect BIPV's performances, the curved-shape façade's orientation is approximated as follows: south (S), south-east (SE) and south-west (SW). The Swedish electricity mix (SE) and European electricity mix (EU) are explored in the comparison.

The BIPV system's carbon footprint is dominated by the CIGS module with 70 % of the impacts, while mounting accounts for 18 % and electric connections to the grid (inverters, cables, etc.) 10 %. The BIPV's end-of-life makes up approximately 1 % (only collection and sorting are included). No recycled material is accounted as a benefit at end-of-life since we consider a steady state system (identical recycled material input and output). Compared to the BIPV-system-equipped façade, the cement-tile façade impacts that are ten times lower. For electricity production, the alternative scenario with a Norwegian mix points out that the BIPV installation worsens carbon emissions, while it is extremely beneficial when compared to the EU mix. This is due to the low kWh carbon footprint of electricity in Sweden (34 gCO_2eq/kWh, while EU's kWh carbon footprint is ten times higher with 360 gCO_2eq/kWh).

Interpretation:

The results are partly based on assumptions. Modules, inverters, mounting system and conventional material's environmental impacts are based on generic life cycle inventories. Monthly module irradiation is estimated using the PVGIS software. KWh carbon footprint is also assessed on a monthly basis in order to avoid bias. Both performance ratio and degradation factors are based on default values commonly used in scientific articles. The performance ratio (PR) particularly needs further investigation since it is based on empirical data. However, the default value for performance ratio is sometime questioned by scientists, especially as façade systems are concerned. Indeed, dust, soiling shadow and potential inverter breakdown or cabling issues (for example) are not considered and can lead to a reduced performance ratio. More accurate performance ratios should be calculated and some publications suggest that PR is sometime lower than 0.7.for BIPV façades. Lifetime is also an important aspect. A module's estimated lifetime is typically 30 years. Nevertheless, building engineers and architects suggest that a longer lifetime can be relevant as soon as the building's function is fulfilled. Indeed, modules' efficiency after 30 years typically amounts to 80 % but decreases only down to 70 % after 50 years (which corresponds the building's lifetime). For a building, such a small difference does not justify a replacement, provided that the building's function is fulfilled. BIPV systems' environmental footprint could be strongly enhanced with a longer life time. The decision of a market (EU) mix versus a national grid mix when assessing BIPV's environmental performance is crucial. Indeed, Sweden has a significant low-footprint electricity and is at the same time a big exporter of electricity. An increase of the renewable-energy capacity improves the overall electricity market and not worsen Sweden's grid mix. The choice of the grid mix needs to be considered carefully in order to fairly reflect the environmental performance of a BIPV system installed in Sweden.

Conclusions:

The Frodeparken building has a good exposure and CIGS BIPV modules installed on a large surface. Energy production data are now collected and are coherent with the modelling. Conventional electricity's mix remains a key question as for environmental performances are concerned. Sweden being an electricity net exporter, it is therefore suggested that an increase in electricity production led to higher expert and shall be compared to the market mix. This is a crucial issue since carbon payback time (CPBT) calculated with the European (market) grid mix is 7 years but is 60 years (twice the lifetime of the BIPV) when calculated with the Swedish grid mix.

5.9. BIPV façade of the Office building in Olso (Norway)

The Office Building is a typical construction with a BIPV façade which 'theoretical' location is Oslo. This typical four-storey tertiary edifice was designed so as to assess/investigate a Zero Emission Buildings concept. The façade faces south and has a surface of 255 m^2 of mono-Si PV (156 modules) corresponding to a power system of 22 kWp. A majority of the data stems from a report describing the building (Dokka et al. 2013). Additional data was provided directly by the study authors.

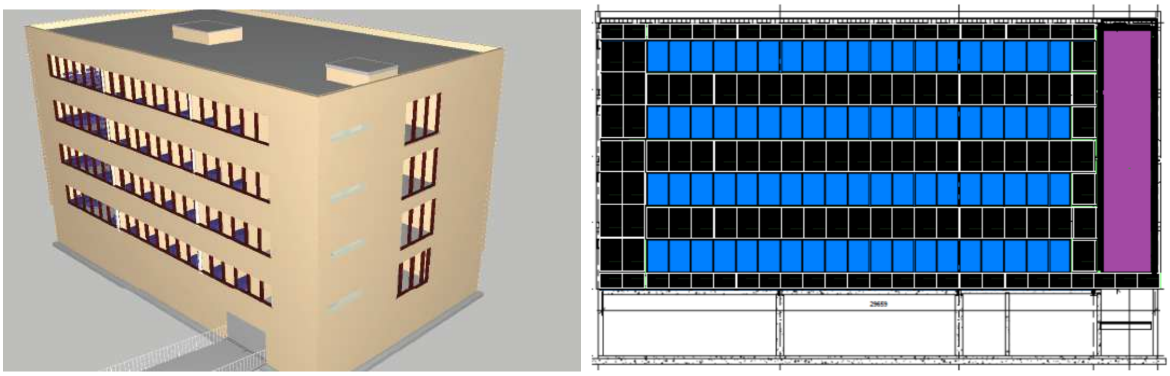

Figure 21 a and b: Office Building (a); BIPV layout (b) (from (Dokka et al. 2013)

Functional unit: 1 m^2 of building façade during 1 year. Requirements: the system shall fulfil both building function and electricity production during 30 years.	
Reference scenario: 1 m^2 of Building-Integrated PV system producing 120 kWh of electricity.	Alternative scenarios: Conventional building skin material for 1 m^2. Electricity production corresponding to 1 m^2 of BIPV on average during one year (120 kWh) produced with the Norwegian or European grid mix for year 2016 using ENTSOE data.
System boundaries: Modules, BOS, mounting and edging, system's end-of-life. No potential end-of-life recycling system extension is included.	Conventional material is considered for the building's function. Electricity produced by the grid in 2016 (reference year) is included.
Technical description: The BIPV installation consists in a 255 m^2 façade cladding facing south, made of mono-Si modules. Tilt: 90 ° Module efficiency: 20 % Installed capacity: 22 kWp Inverters power: 22.8 kW Performance ratio: 0.75 Packing factor: 0.93 Annual degradation: 0.7 %	The building skin's conventional material is a cement-tile façade. Alternative (a): the Norwegian monthly grid mix (including imports) is used for assessing electricity production's impact on the environment. Alternative (b): the monthly market mix (European) is used for assessing electricity production's impact on the environment. Total irradiation received on the module plane per year: 960.3 kWh/m^2. Total energy output over 30 years: 3 617 kWh/m^2
Data sources: irradiation data are assessed using the PVGIS software (JRC, Ispra). Activity data are mainly from the project's report. All background data originate from ecoinvent 3.5.	

Impact assessment:

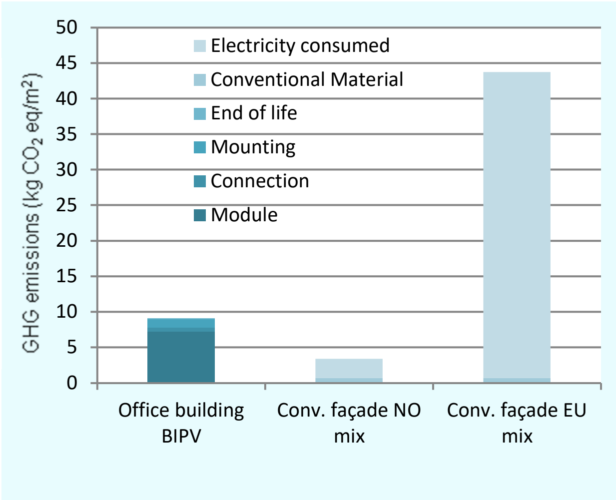

Figure 22: Comparison of GHG emissions of the BIPV system per m² during one year with the alternative scenarios where electricity is produced with a Norwegian mix. The Norwegian electricity mix (NO) and the European electricity mix (EU) are explored in the comparison.

The BIPV system's carbon footprint is dominated by the mono-Si module with 80 % of the impacts, while mounting accounts for 6 % and electric connections to the grid (inverters, cables, etc.) 13 %. The BIPV system's end-of-life makes up approximately 1 % and only includes collection and sorting. No recycled material is accounted as a benefit at end-of-life since we consider a steady state system with an identical recycled material input and output. Compared to a BIPV-system-equipped façade, the cement-tile façade shows impacts that are thirteen times lower. For electricity production, the alternative scenario with a Norwegian mix points out that the installation of BIPV worsens carbon emissions, while it is very beneficial when compared to the EU mix. This is due to kWh's small carbon footprint in Norway (22 gCO_2eq/kWh) while EU's kWh has a higher footprint (360 gCO_2eq/kWh).

Interpretation:

The results are partly based on assumptions. Modules, inverters, mounting system and conventional materials' environmental impacts are based on generic life cycle inventories. The monthly module irradiation is estimated with the PVGIS software. KWh's carbon footprint is also appraised on a monthly basis in order to avoid any bias during the environmental assessment. Both performance ratio and degradation factors are based on default values commonly used in scientific articles. The performance ratio particularly needs further investigation since it is sometimes questioned by scientists, especially as for façade systems are concerned. Indeed, dust, soiling shadow and potential inverter breakdown or cabling issues (for example) are not considered and can lead to a reduced performance ratio. The modules lifetime can be 50 years instead of 30 years, provided that the building's function is fulfilled. In this case, the BIPV system's environmental performance increases by 50 %, since modules' efficiency is expected to be 70 % after 50 years. The choice made between a market (EU) mix and a domestic grid mix is crucial when appraising the environmental performance of BIPV. Indeed, Norway is an important electricity exporter of electricity at very low footprint. An increase in its renewable energy production capacity improves the overall market electricity mix and not worsen Norwegian's grid mix. Since Life Cycle Assessment does not take into account exported electricity's environmental benefits, assessing BIPV's environmental performances using a market (European) grid mix better reflects Norway's actual future BIPV installations consequences. Such a decision can lead to striking differences in the result of BIPV's carbon payback time (CPBT). Calculation based on the market grid mix (Europe) gives a CPBT of 6 year while it reaches 100 years if the Norwegian mix is used in the calculation (widely exceeding the lifetime of the PV).

Conclusions:

The Office Building is another illustration of a fully theoretical building allowing to test the potential environmental performance of a façade-integrated PV system. The main question raised by the case study is the choice of the conventional grid mix for comparison. Using the market grid mix suggests that the BIPV system is extremely eco-friendly; but the same assessment with a country grid mix engenders opposite conclusions.

5.10. BIPV balustrade of the Lasa house in Italy

The Lasa house is a single-family home located in Lasa, Italy. PV modules are installed on the roof and BIPV modules act as a balustrade on the balcony. The house has a large view on the surrounding landscape on south, which motivate the installation of a semi-transparent balustrade. Frameless modules are fixed using the same mounting structure as for conventional glass balustrades. Six modules cover a total surface of 13 m^2. The system' total installed capacity is 1.3 kWp. The case study is presented in detail in a book (Maturi et Adami 2018).

Figure 23: Lasa house (a); BIPV balustrade layout (b) (Photo from Maturi and Adami 2018).

<table>
<tr><td colspan="2"><u>Functional unit</u>: 1 m^2 of balustrade during 1 year.
<u>Requirements</u>: the system shall fulfil both building function and electricity production during 30 years.</td></tr>
<tr><td><u>Reference scenario</u>:
1 m^2 of Building-Integrated PV system producing 87 kWh of electricity.</td><td><u>Alternative scenarios</u>:
Conventional building skin material for 1 m^2. Electricity production corresponding to 1 m^2 of BIPV on average during one year (87 kWh) produced with the Italian or European grid mix for year 2016 using ENTSOE data.</td></tr>
<tr><td><u>System boundaries</u>:
Modules, BOS, mounting and edging, system's end-of-life. No end-of-life recycling system extension is included.</td><td>Conventional material is considered for the building's function. Electricity produced by the grid in 2016 (reference year) is included.</td></tr>
<tr><td><u>Technical description</u>:
The BIPV installation consists of a 13 m^2 semi-transparent balustrade facing south, made of mono Si cells.
Tilt: 90 °
Cell efficiency: 18.7 %
Installed capacity: 1.3 kWp
Inverters power: 1.5 kW
Performance ratio: 0.75
Packing factor: 0.625
Annual degradation: 0.7 %</td><td>The building skin's conventional material is a glass balustrade.
Alternative (a): the monthly Italian grid mix (including imports) is used for assessing electricity production's impact on the environment.
Alternative (b): the monthly market mix (European) is used for assessing electricity production's impact on the environment.
Total irradiation received on the module plane per year: 1 100 kWh/m^2.
Total energy output over 30 years: 2 603 kWh/m^2.</td></tr>
<tr><td colspan="2"><u>Data sources</u>: monthly irradiation data are assessed using the PVGIS software. Activity data are provided by the building engineers. All background data are from ecoinvent3.5.</td></tr>
</table>

Impact assessment:

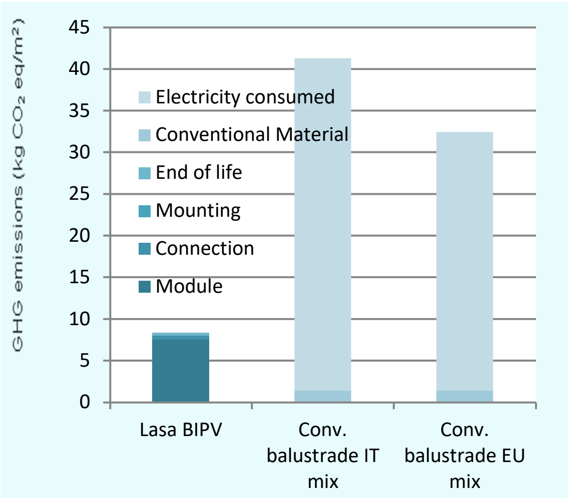

Figure 24: Comparison of the GHG emissions of the BIPV balustrade per m² during one year with the alternative scenarios where electricity is produced by the Italian mix. Italian electricity mix (IT) and European electricity mix (EU) are explored in the comparison.

The irradiation simulation indicates that the Lasa house is well located in the mountains with a significant irradiation. The system is therefore environmentally interesting. In terms of impact, the BIPV system is dominated by the module with a share of 90 %. But this is partly due to the fact that there is no BIPV-specific mounting system (same system as for the passive glass balustrade). Grid connections account for approximately 6 % of the impacts and the end-of-life nearly 4 % (mainly due to weighty glass modules transportation). No recycled material is accounted as a benefit at the end-of-life since we consider a steady state system with the same input and output of recycled material.

The passive glass balustrade has 6 times less impact due to its small thickness and the absence of solar cells. Italian and European grid mixes present similar performances.

Interpretation:

The results are partly based on assumptions. Modules, inverters, mounting system and conventional materials' environmental impacts are based on generic life cycle inventories. Monthly module irradiation is estimated using the PVGIS software. Carbon footprint (per kWh) is also assessed on a monthly basis so as to avoid any bias during the environmental assessment. Both performance ratio and degradation factors are based on default values commonly used in scientific articles. The performance ratio particularly needs further investigation. The packing factor needs special attention for semi-transparent BIPV systems. Indeed, semi-transparent systems need to find the best solution (i.e. producing PV electricity while letting light pass through the balustrade). The ratio between the active surface and the total surface of the module can vary by a factor of two or three, directly affecting the efficiency of the module. Lifetime of the system (here 30 years) also affects the system's environmental performance. Indeed, when PV reach the building's lifetime, their environmental performance rises up to 50 %. Carbon payback time (CPBT)'s calculation (as an environmental performance indicator) shows that the balustrade compensates carbon emissions (caused by the production) within 7 or 8 years.

Conclusions:

The BIPV balustrade tested in the Lasa house is a good example of semi-transparent PV. Even though the BIPV system presents a rather high footprint, it remains profitable for the environment. In terms of electricity production, Italy is currently an electricity net importer, which suggests that the country mix shall be more relevant. Still, in both cases the system presents a promising carbon footprint.

5.11. BIPV façade of the Fronius building in Wels (Austria)

The Fronius building is a solar glass building with a double-skin façade enabling the integration of 660 m^2 of semi-transparent PV modules. The construction is located in Wels, Austria. The PV modules cover three façades, with 132 m^2 for the south façade and 264 m^2 for the east and the west façade. Altogether, the envelope is made of 146 glass façade elements produced by Ertex Solar. The building includes solar glass PV both on the roof and the façade, but only the semi-transparent façade is analysed in the case study.

Figure 25: Fronius building (a); BIPV view (b).

<table>
<tr><td colspan="2"><u>Functional unit</u>: 1 m² of building façade during 1 year.
<u>Requirements</u>: the system shall fulfil both building function and electricity production during 30 years.</td></tr>
<tr><td><u>Reference scenario</u>:
1 m² of Building-Integrated PV system producing which can be located on south, east or west façade and producing respectively 39 kWh south, 29 kWh west and 28 kWh east façade .</td><td><u>Alternative scenarios</u>:
Conventional building skin material for 1 m².
Electricity production equivalent to the one produced by the BIPV in the reference scenario and produced with the Austrian or European grid mix for the year 2016 using ENTSOE data.</td></tr>
<tr><td><u>System boundaries</u>:
Modules, BOS, mounting and edging, system’s end-of-life. No end-of-life recycling system extension is included.</td><td>Conventional material is considered for the building’s function. Electricity produced by the grid with 2016 as the reference year is included.</td></tr>
<tr><td><u>Technical description</u>:
The BIPV installation consists of a 660 m² semi-transparent façade facing south (132 m²), west (264 m²) and east (264 m²), made of mono Si PV.
Tilt: 90 °
Cell efficiency: 17.3 %
Installed capacity: 31 kWp
Inverters power: 30 kW
Performance ratio: 0.75
Packing factor: 0.378
Annual degradation: 0.7 %</td><td>The building skin’s conventional material is a glass façade.
Alternative (a): the monthly Austrian grid mix (including imports) is used for assessing electricity production’s impact on the environment.
Alternative (b): the monthly market mix (European) is used for assessing electricity production’s impact on the environment.
Total irradiation received on the module plane per year for each façade is 32.9 kWh/m² (S), 13.3 kWh/m²(W), 14 kWh/m² (E).
Total energy output over 30 years per façade is 1 161 kWh/m² (S), 875 kWh/m² (W), 850 kWh/m² (E).</td></tr>
<tr><td colspan="2"><u>Data sources</u>: monthly irradiation data are assessed using the PVGIS software. Activity data are provided by the building engineers. All background data originate from ecoinvent 3.5.</td></tr>
</table>

Impact assessment:

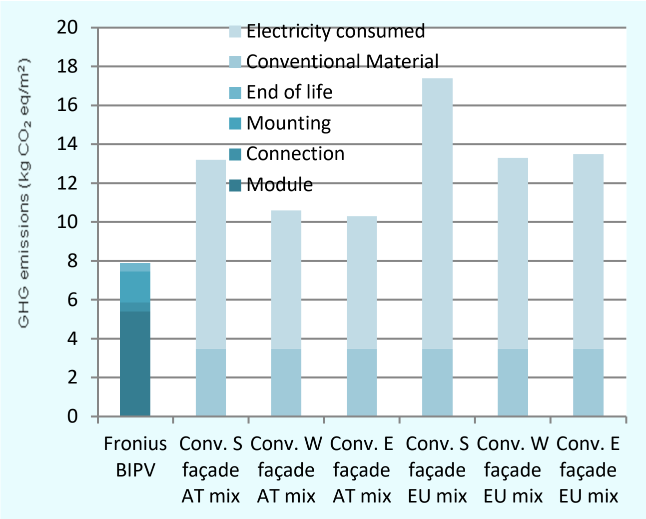

Figure 26: Comparison of the GHG emissions of the BIPV system per m² during one year with the alternative scenarios where electricity is produced by the Austrian mix for the south (S), the west (W) and the east (E) façade. Both Austrian electricity mix (AT) and European electricity mix (EU) are explored in the comparison.

Carbon footprint seems favourable to the BIPV system. Per square meter of BIPV, the south-facing façade is 25 % better than the east and the west façade. The BIPV system's carbon footprint is dominated by the module with 68 % of the impacts, while mounting accounts for 20 % and electric connections to the grid (inverters, cables, etc.) 6 %. The system's end-of-life share is approximately 1 % and only includes collection and sorting. No recycled material is accounted as a benefit at end-of-life since we consider a steady state system with the same input and output of recycled material. Compared to the BIPV system, the glass façade presents approximately one half of the impacts. This is due to solar cells and reduction of glass' thickness and treatment. As for the carbon footprint, the alternative scenario with an Austrian and a European mix shows coherent figures.

Interpretation:

The results are partly based on assumptions. Modules, inverters, mounting system and glass façades' environmental impacts are based on generic life cycle inventories. Monthly module irradiation is estimated using the PVGIS software. Carbon footprint (per kWh) is also assessed on a monthly basis so as to avoid any bias during the environmental assessment. Both performance ratio and degradation factors are based on default values commonly used in scientific articles. The performance ratio particularly needs further investigation since it is sometimes questioned by scientists, especially as for façade systems are concerned. Indeed, dust, soiling shadow and potential inverter breakdown or cabling issues (for example) are not considered and can lead to a lower performance ratio. Façade systems actual performance ratio (PF) statistical data is missing if we want to weigh the potential variability due to this parameter. This needs further developments since existing publications suggest that PF sometimes decreases close to 60 % for BIPV façades. The packing factor needs special attention. Indeed, while opaque BIPV solutions present very similar packing factors (varying from 0.88 to 0.98), semi-transparent systems are very dependent on packing factor. Indeed, semi-transparent systems need to find the best trade-off between producing PV electricity while letting light pass through, fostering the use of thinner semiconductor surfaces (reducing efficiency) or encouraging the reduction of cell surface in the module (reducing the packing factor). The packing factor's integration in the overall calculation of the system's environmental performance is a key aspect. Moreover, the system's lifetime (here 30 years) could be closer to the building's life span, since building function (double skin façade) can last very long. In this case, a PV lifetime increase leads to a PV footprint decrease (a lifetime of 50 years instead of 30 would increase the environmental performance by 50 %).

Conclusions:

The Fronius building is made of semi-transparent façade-integrated PV in very large unframed windows. Despite a large area of building covered, both active PV material surface and electricity production are limited. As a consequence, calculations show that for the western and the eastern façades, the carbon payback time (CPBT) can reach 24 years (Austrian grid mix) instead of the 25 years indicated in PV panel manufacturers' technical datasheets. This means that even though BIPV façades are a good energy-producing solution, the entire lifetime of the BIPV does not always engender carbon savings. It just recovers in24 years, the carbon emitted in a few months during the modules production.

6 Comparison between case studies

One of the objectives of the work is to demonstrate that the environmental impacts of BIPV can be quantified in a comparative framework. For this purpose, we consider in this section comparisons of building skin solution with or without BIPV; comparison of the environmental interest of BIPV within each category of BIPV systems, and the comparison of all BIPV without considering the energy produced during the use phase.

6.1. Comparison between BIPV systems for opaque roofs

Each BIPV category has different technical requirements. Mounting BIPV on façades is more impactful than mounting on roof and the semi-transparent systems needs to manage a trade of between producing electricity and enabling daylight in the building.

It is therefore relevant to compare BIPV including their performances on energy production at the category level following categories presented in the section 3.1.

For opaque roofs, 4 BIPV solutions are compared below.

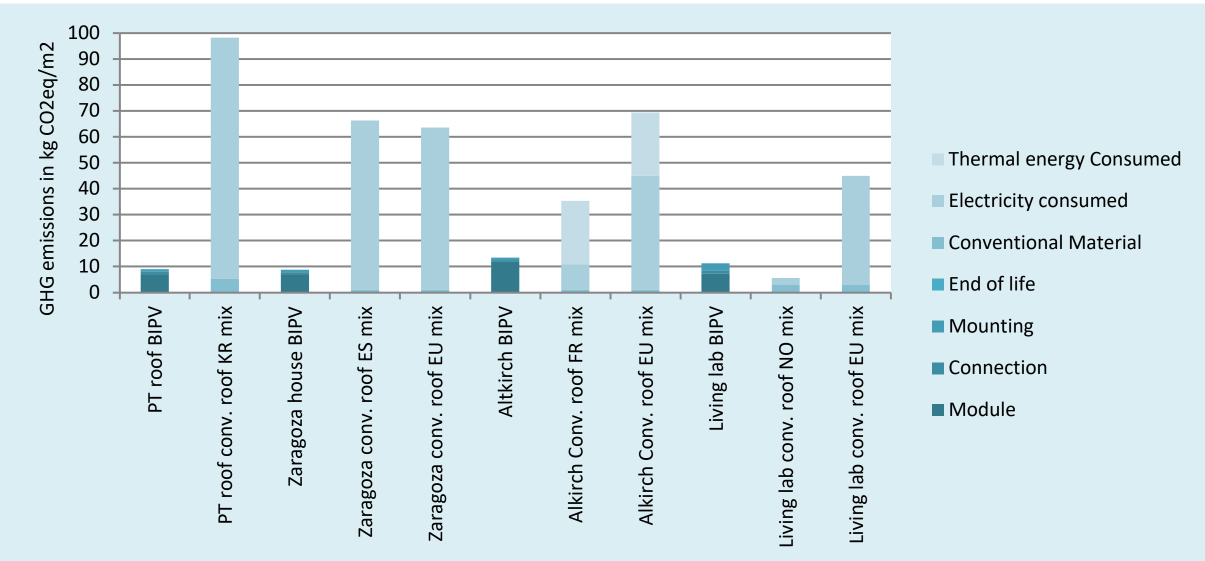

Figure 27: Comparison of the annual carbon footprint of opaque roof conventional building skin with BIPV solutions per square metre. Eleven situations are compared with 4 different technologies installed on four different buildings in Korea (PT Roof), Spain (Zaragoza), France (Altkirch) and Norway (living lab). A building is tested with different situations when several orientation or electricity mixes are possible for a building. For each comparison, the solution with the BIPV is presented and compared with its alternative with conventional material (if no BIPV is installed). The impact of the BIPV can then be compared with the impact of the material which might otherwise have been used for the building skin, the electricity produced and the thermal energy produced in the conventional situation.

The carbon footprint of the BIPV as a product does not vary a lot between the different solutions (only a factor 1.5 between Altkirch and Zaragoza), while the impacts in all conventional solutions can vary by a factor 15. It means that the environmental performance of the BIPV depends on its environment, its efficiency and then on its own impact. The electric grid mix at the BIPV location is the first driver of the environmental performance. The differences in the electricity mixes are dominating the differences in efficiency. The PT roof system is running a multi-Si BIPV system with an efficiency of 14 % which receives a yearly in-plane irradiation around 1 500 kWh/m^2. The Living lab roof has an efficiency of 15.8 % with a yearly irradiation of 1 200 kWh/m^2. Despite the fact that the efficiency of the Living Lab is higher than the PT roof system and that it receives 25 % less irradiance. The installation of 1 m^2 of the BIPV system on the Korean building enable a reduction of carbon emissions by a factor 11 compared to the conventional building component while the reduction is only a factor 4 in Norway (considering the EU mix). The carbon footprint of the kWh of the electricity network in both countries explains this difference, using one kWh in Korea emits 715 gCO_2eq/kWh while it emits 360 gCO_2eq/kWh in Europe. This also explains the small difference between Spanish and European mix with Zaragoza house. The key influence of electricity mixes put in light the surprising situation of Norway. The Norwegian mix is emitting about 20 gCO_2eq/kWh. Installing BIPV for competing with Hydropower in Norway is counter performing in terms of reduction of CO_2 emission. Since Norway is a big exporter of electricity, installing BIPV systems in Norway reduces the carbon footprint of the European grid mix, indeed Norway exports on average 15 % of its electricity production**.** The last important point of Figure 27 is the performances of the hybrid module. Indeed, saving thermal energy as well as electric power allow a better use of the surface availability on the building. This is reflected with the reduction by a factor 3 of the carbon footprint of one square meter of building envelope.

Among all the BIPV categories, the opaque roof is the optimal solution (i.e. best environmental performance). Indeed, opaque roof installations are easier than other PV installations, with well-known installation systems and good irradiation allowing considerable electricity production.

From a more general standpoint, considering the modelling assumptions, we can see that it is useful to work at the level of a category instead of the level of all BIPV. This is clearly illustrated with the opaque roof category. It also helps to understand how to improve classification. For example, a distinction between flat roofs and slanted roofs seems not necessary, but a distinction between BIPV and BIPV-T shall be made because of the difference in modelling assumptions.

6.2. Comparison between BIPV systems for opaque façades

Five different solutions are explored with 4 PV technologies and presents 20 different situations varying on the basis of the façade orientation or the electricity mix.

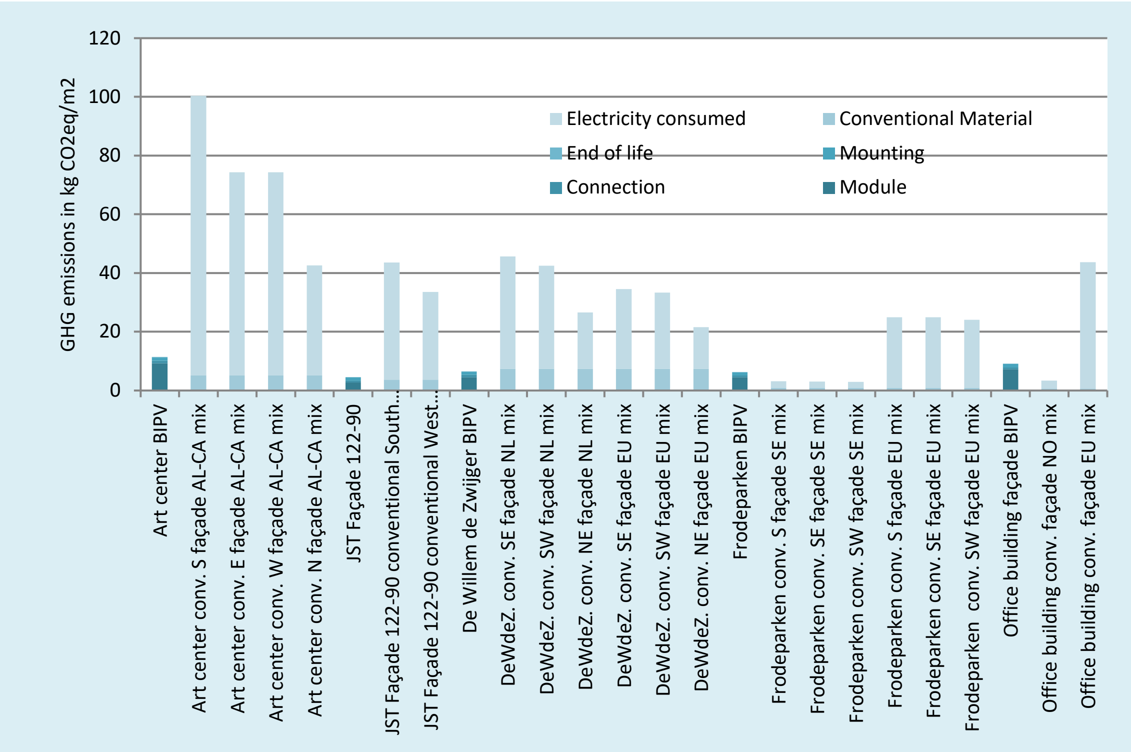

Figure 28: Comparison of the annual carbon footprint of opaque façade per square metre for 24 different situations. 5 buildings façades in Canada (Art centre), Korea (JST building), Netherland (De Willem de Zwijger), Sweden (Frodeparken) and Norway (Office building) are studied. The variants explored are façades with BIPV or façades with conventional building skin with different orientations and electricity mixes.

The calculation for Alberta illustrates the influence of the orientation of the façade. The Art centre building is covered with BIPV on its 4 façades. The south and the north façades receive very different irradiation levels. The reduction of CO_2emissions by the BIPV system compare to the conventional scenario differs by a factor of 2.5. Nevertheless, due to the high carbon value of Alberta's electricity (705 gCO_2eq/kWh), the reduction of carbon emission is close to a factor of 10 for the south façade and a factor of 4 for the north one. Korean solutions seem even more efficient with a reduction of carbon emissions by a factor of 10. The three other buildings are in Europe and the difference is less important since the grid mix has a lower carbon content. As mentioned for roofs, we can nevertheless observe that a BIPV installation in Sweden or Norway actually reduces CO_2 emissions compared to the conventional scenario only if the installation contributes to export more and greener electricity to other countries.

The case studies show that façades can represent large area, and considering the number of building that can receive BIPV façade, the market of BIPV can be important. Another interesting outcome is that the eastern and western façades have a rather high production yield and allow smoothing the daily solar installed capacity. Indeed, higher irradiation levels in the morning and during the afternoon allow an electricity production earlier and later during the day. Nevertheless, this environmental strength is currently not reflected by the environmental performances of BIPV since the assessment of the carbon footprint for conventional electricity is based on monthly mixes observed in the past. An hourly mix study would bring to the fore the effects of morning and evening façade BIPV electricity production. The second observation pertains to the BIPV technology being considered. Among the great variety of technologies explored, the CIGS technology seems to be very interesting from an environmental perspective. It combines both a small production footprint and a rather high efficiency. In terms of limitations, one shall bear in mind that the performance ratio used here is based on empirical values originally based on roof studies (Perez et al. 2012; IEA-PVPS-T2-01:2000 2000) and is likely to overestimate the environmental benefit. At the same time, façade cleaning and repairing are not considered but can affect the overall footprint. More in-depth studies are necessary.

6.3. Comparison between BIPV systems for semi-transparent façades

Semi-transparent BIPV is a more complicated system since it has to find the best trade-off between saving daylight and producing energy. Two different solutions of semi-transparent BIPV façades are assessed. Both are based on mono-Si but with different types of modules.

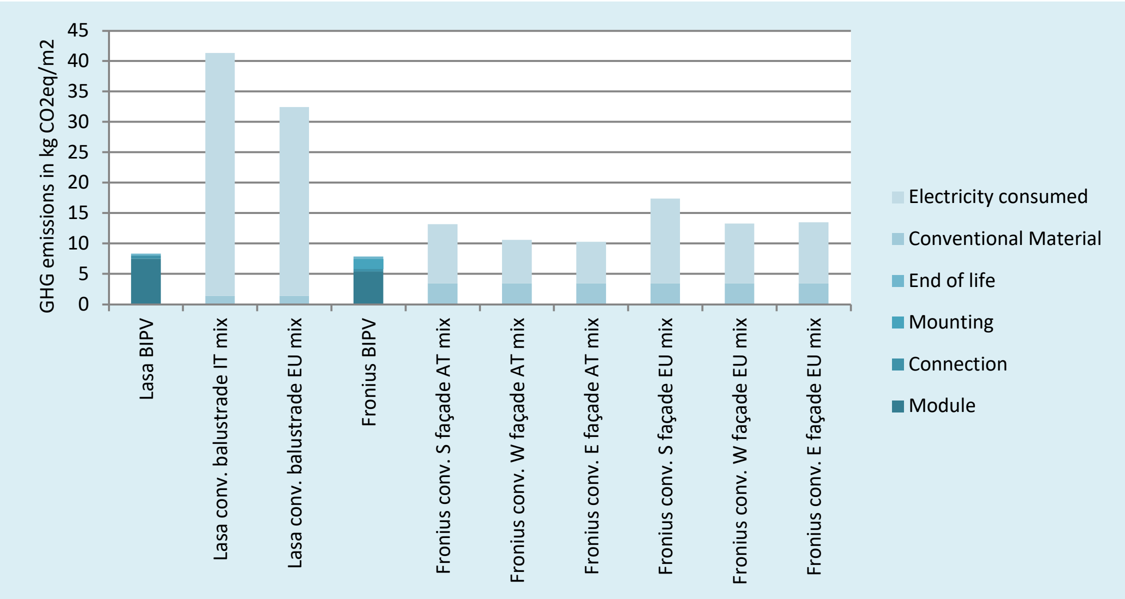

Figure 29: Comparison of the annual carbon footprint of façade per square metre for 10 different situations based on 1 building façade in Lasa (Italy) and 3 different façades in Wels with the Fronius building in Austria. The variants explored are façades with BIPV or façades with conventional building skin with different orientations and electricity mixes.

The Lasa house is assessed with only one orientation (south) and two different electricity mixes. The carbon footprint of Italian kWh is higher than the European one. For this reason, the carbon footprint of a conventional solution using the country mix in Italy has more impact than one using the market (European) mix. We can see exactly the opposite for Austria where the conventional solutions with the European mix seems more impactful than the Austrian one. The comparison between the different orientations for the Austrian building shows that east and west oriented BIPV is 25 % less efficient in mitigating carbon emissions than south oriented one. A comparison can be done between BIPV within one category. The environmental GHG emissions reduction between the conventional scenario and the BIPV one is of a factor 3.9 for Lasa house and 2.2 in the Fronius building for the south façade (1.7 for east or west façades) assuming the system depends on the European grid.

Although not the most productive solution, semi-transparent BIPV is very promising (i.e. large surfaces on a multitude of tall buildings) as described in existing studies (Defaix et al. 2012; Eiffert 2003). Nonetheless, we can see that durability requirements, glass solar panel efficiency and packing factor strongly influence the overall footprint of the system (Agathokleous, Kalogirou, et Karellas 2018; Tripathy, Sadhu, et Panda 2016; Cucchiella et D'Adamo 2012; Vats, Tomar, et Tiwari 2012; B. Agrawal et Tiwari 2011). The two case studies as well as the simulation of possible Carbon Payback Time presented in section 6.5 highlight that such BIPV can present long CPBT. Increasing the number of case studies would help to better understand this issue.

6.4. Comparison between BIPV systems without energy production

The calculation of the carbon footprint of BIPV allows a comparison of different types of BIPV. Provided that the functional unit, the system boundaries and the characterisation model are the same for assessing all BIPV, it is possible to compare directly the carbon footprint of all BIPV on the basis of their production and their end of life. Results are presented below as GHG emissions per square metre of BIPV and assuming that the life time of BIPV is always 30 years.

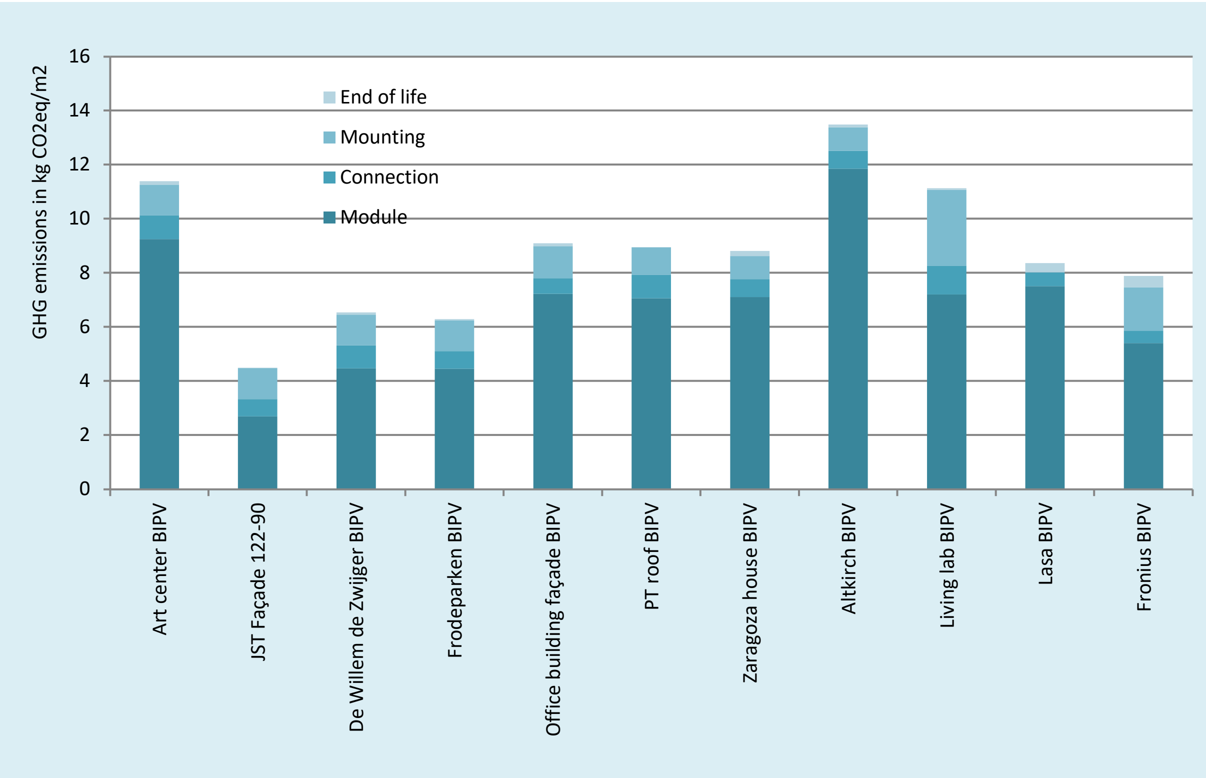

Figure 30: Comparison of the annual carbon footprint of the 11 BIPV systems of the case studies per m² of BIPV. Production, replacement of inverters and end-of-life of all subpart of the system are taken into account. The BIPV system includes the module, the electric connection with the grid and the mechanical connection with the building. All systems are fully integrated in each building.

The BIPV presenting the smaller impact is the amorphous silicon aluminium with carbon emissions of 4.5 $kgCO_2eq/m^2$. On the opposite, the one presenting the higher impact is the hybrid PV since its function for thermal and electric energy requires more material and processes for its production, its emissions are more than 13 $kgCO_2eq/m^2$. Comparison between BIPV systems is driven by the modules. The ranking of BIPV on the basis of their impacts strictly follow the technologies. a-Si technology has the smallest GHG emissions per m^2, then followed by CIGS, then by multi-Si and then mono-Si. BIPV-T based on mono-Si presents the highest GHG emissions. The carbon footprint depends on the level of purity of the silicon (except for CIGS where electricity for applying semi-conductor is the key parameter). These results do not cover the use phase. A complete assessment taking into account BIPV's electric productivity can modify the ranking.

6.5. Comparison of the carbon payback time of BIPV systems

This section aims at calculating the CPBT for comparing environmental performances of the 20 BIPV installations with the 11 case studies addressed in the work.

Energy payback time (EPBT) is a very common measure for addressing the energy performance of a PV module. The value is typically expressed in years. It is the ratio between the energy produced per year by a module and the energy needed to produce it. If the EPBT is very small, then the PV module will produce far more energy compared to the energy that was needed for its production. The calculation of EPBT presented here is a simplified method and is based on final energy, while with other methods the calculation can be based on primary energy (Frischknecht et al. 2016).

Environmental awareness of building owners led to elaborate the Carbon Payback Time (CPBT) which is based on a similar meaning, reflecting the number of years which are necessary for a PV module to mitigate the same amount of carbon that the one emitted during its production. Of course, the CPBT depends not only on the module performance, its impact at the production and its irradiation, but also on the electricity mix of the area of production and the electricity mix of the area of installation. A module with a short CPBT can be considered as environmentally-friendly for its carbon footprint while a module with a high CPBT has a high carbon footprint. If the CPBT exceeds the lifetime of the PV, then the PV can present a net positive carbon footprint. Figure 31 compares CPBT of different BIPV systems.

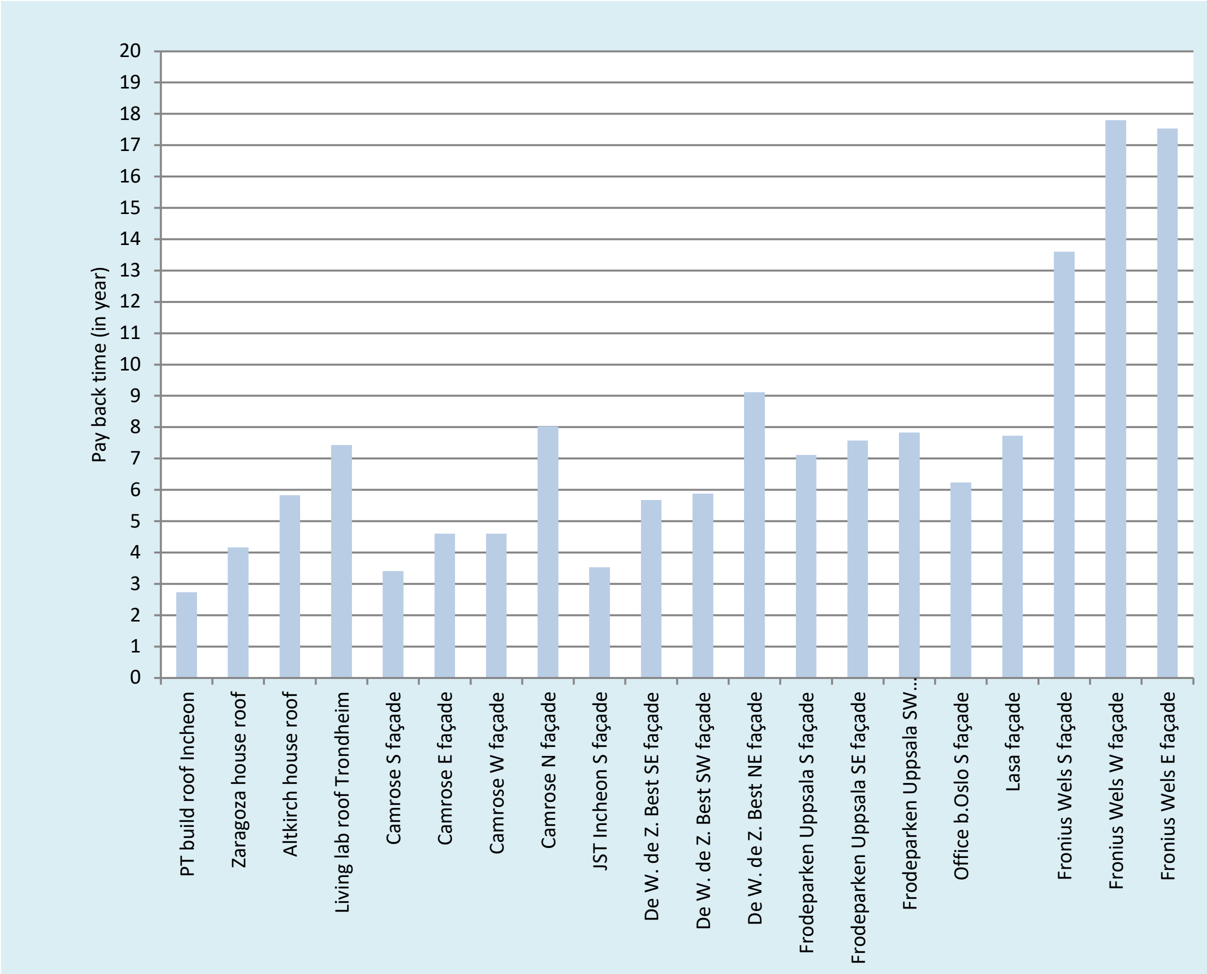

Figure 31: Comparison of the Carbon Payback Time of 20 different PV modules installed in different situations (Country, cities, orientation, tilt, technologies, etc.). Low CPBT indicate a high potential in reducing GHG emissions while the high CPBT reflect a low mitigation potential. Each BIPV can have a south (S), east (E); west (w) or north (N) orientation. The electricity mix used to assess the payback time value is the market mix (Alberta's mix, Korean mix and European mix, for the year 2016).

Calculated carbon footprint of BIPV systems range from 2.7 years (for PT building in Korea) to nearly 18 years (for Fronius building in Austria). The main driver of the CPBT is the carbon footprint of the kWh of the electricity grid, substituting electricity in Korea (715 gCO_2/kWh) which is far more efficient than doing the same in Europe (360 gCO_2/kWh). The orientation of the BIPV system is crucial, on Camrose building (Alberta, Canada) the CPBT is about 3 years on the south façade but goes up to 7.5 years when exposed to the north. It is also strongly dependent on the design of the BIPV, this is visible with the semi-transparent BIPV façades comparing the Lasa house and the south façade of the Fronius building. The CPBT are 7.5 and 13.5 years respectively, while the cells technology, the orientation, the tilts and the grid mix are the same. The east and the west façades of the Fronius building take about 18 years to recover the carbon emitted during their production, and their lifetime mentioned by the manufacturer is 25 years. So even if this BIPV system can be favourable on an energy production perspective, its relevance for reducing burden on climate change is questionable.

7 Selection of the key modelling parameters

The case studies allow the analysis of numerous parameters. Among all, some parameters are crucial for modelling. They are presented here.

The usefulness and the applicability of several descriptors used to characterize BIPV were studied in the project such as (module, system, situation, connection to the network, description of grid mix specificities).

Some of them are suited for characterizing BIPV for a LCA study and are presented below following the three steps that are required for modelling BIPV performance to enable a LCA study:
1- the calculation of the irradiation received by the system;
2- the energy (electric or thermal) produced;
3- the environmental benefits due to the connection to the electricity grid.

7.1. Irradiation data

The irradiation data are expressed as kWh of yearly irradiation received on the module plan per square metre of module. It depends on the following parameters:
- the location: assumption or actual at the area level (city) or the point (GPS data). In case the irradiation is as a default value for a given area, a location used as reference of this area shall be chosen (such as a reference city for a country).
- the tilt: standard depending on the building solution (slanted roof, flat roof. façade) or statistical or measured (observed) in an actual building.
- the orientation: standard (possibly based on optimum or statistical values) and then possibly optimum or statistical or observed in an actual building
- the environmental conditions of the installation: optimum, or statistical, or empirical or observed. It includes, dust, soiling, shadow, pollution, etc.). The environmental conditions are typically included in the appraisal of the "capture losses" of the system.

A direct measure of the irradiation of the BIPV system is possible, in that case the monitoring of the irradiation corresponds to an average irradiation over a certain time period. If no monitoring is done, an estimation of the irradiation can be done using existing software. As an example, PV GIS was used for assessing the irradiation for some case studies. Nevertheless several countries such as Korea or Canada are not covered by the software and are from other sources.

Irradiation data can be collected or calculated at several time steps. Annual irradiation data are typically available. Nevertheless, monthly data avoids overestimating the environmental performances of the BIPV system. Indeed, the carbon footprint of the kWh vary with time over the year and over the day. Seasonal variation can be resolved with monthly data. Hourly data can be used as well to avoids bias due to daily variation. Nevertheless, this short time step is rarely available and requires to manage a large amount of data in the calculation.

7.2. Electricity production

In some cases, this electricity produced from irradiations is directly and continuously measured as an output of the BIPV system, and sometimes at very short time steps. In that case, this data can be used directly for LCA and irradiance measurement is not necessary. Even modelled data of electricity production can be used on a monthly time step or on an annual time step.

If electricity production data are not available, the modelling of electricity production shall be done with an estimation of the module efficiency in standard conditions, and an estimation of the system losses (power regulation, connection, cabling, inverter). The module efficiency is typically provided by the module manufacturer after testing it in standard conditions. The case studies shown that for semi-transparent modules, the module efficiency is sometimes not provided and an approximation shall be done based on the cell efficiency and the packing factor (surface of semi-conductor divided by the module surface). The standard module efficiency shall also be corrected by its degradation over time. The degradation over time is typically included as an empirical data of 0.7 % regardless of the PV technology (Frischknecht et al. 2016). Beyond the module efficiency, the system efficiency shall also be considered. The system efficiency includes all losses due to the electricity management, regulation, conversion, transport, etc. until it enters the grid. Typically, the system losses are approximated to the converter losses or are based on an empirical estimate. Case studies show that approximating the system losses to the inverter losses led to overestimation of electricity produced and underestimation of environmental impacts. Thus, actual data or statistical or empirical values considering all possible losses should be preferred.

Multiplying the irradiation received by the module efficiency (corrected by the degradation factor) and the system efficiency allows the calculation of the electricity production of the BIPV system during the system lifetime. The overall energy produced by the system being divided by the total surface of the system (including edging or flashing surface) allows to calculate the kWh produced per square metre of BIPV system. The electricity output is expressed in kWh of electric energy per square metre of the system.

It shall be noticed that the capture losses (needed for assessing irradiation transformed by the BIPV) and the system losses (needed for assessing electricity production) are the two components of the Performance Ratio. It is therefore easier to assess the electricity of the BIPV system based on its performance ratio (PR) which can be based on-site measures, on detailed parameters, on an estimation of capture losses and system losses, on statistical data or on empirical data.

7.3. Thermal energy production

The specific situation of the Hybrid BIPV-T systems shall also be addressed. In that case the thermal energy production shall be considered. The thermal energy produced can be measured as an output of the system as for the electricity production. It can also be estimated on the basis of the irradiation and the efficiency of the system. Results are expressed in kWh of thermal energy per square metre of the system.

7.4. Modelling the environmental performances of the system

Hence the energy produced by the module is available (electric and thermal energy), the environmental performances of the system can be calculated. As mentioned in the multi-functionality section, we consider that the same amount of energy produced by the BIPV is provided by the electricity network with the conventional scenario. After deciding which electricity network is used in the conventional scenario (e.g. market or country)[4] and after calculating the environmental impact of a kWh from this network, a calculation, covering each energy source and using a LCI database such as ecoinvent, enables to calculate the environmental burden of 1 kWh of electricity from the network. Multiplying it by the number of kWh produced by the BIPV system gives the value of the environmental impact of the energy (electric and thermal energy) that would be used in the conventional scenario. Thermal energy should be modelled on the basis of actual observation.-(possible for refurbishing for example) or statistical data of heating domestic water or air.

[4] The most common approach is to use national mixes as default. Nevertheless, in some cases, the network boundaries are different (smaller or larger) than the physical borders of the country. In a functional approach like LCA. Market mixes can sometime better reflect the functionality of the electricity network when the limits of the electricity network do not fit with the borders of the country. This can happen when a country has several not connected electricity network or when an electricity network is covering several countries and if the energy strategy is running by an authority acting at network level and not at country level.

8 Description of LCA key rules for BIPV

8.1. Definition of the categories of BIPV systems

The classification presented in section 4.1 can be used to define the group of products at which level the modelling parameters are defined. This allows comparing different BIPV systems with comparable results. Nevertheless, learning from the cases studies indicate that a more accurate classification can be done with more case studies. Hybrid systems (BIPV-T) can be modelled as a separate category, and even in BIPV-T one could distinguish between water and air heating. Also, semi-transparent roof is missing and case studies with skylight and veranda for example need to be explored.

In any case the first step for avoiding confusion with communication performances of BIPV systems is to build up a consensual classification and to limits the comparison of BIPV systems within each category. Stand-alone system as well as electricity storage shall be part of this classification.

8.2. Product scope

The product studied is a BIPV system as a building component (sometimes called building material). The Life Cycle Assessment can be conducted at any step of the product’s development and with any level of detail. Indeed, as shown with the Office building and Zaragoza house, fully virtual building can be used for defining irradiation parameters. Also default value of irradiation for a given area and default value of tilt and orientation can be used to assess performances of the BIPV systems. For this purpose, the development of statistical data within each category of product can be useful.

So doing, the BIPV system can be environmentally optimized at each stage of its development. From the early step of the design until a continuous monitoring on the long term.

8.3. System function and multi-functionality of BIPV

The multi-functional aspect of BIPV is a major determinant of the environmental modelling of BIPV and is the unique difference with BAPV. The BIPV system is multi-functional, thus the "*main function*" and the "*additional function(s)"* shall be defined. Since PV is integrated in the building, the "*main function*" of the system is the building function while the energy production is considered as the *"additional function"* (which corresponds to one additional output in case of BIPV or two additional outputs in case of BIPV-T). As required by ISO, LCA shall take into account all the outputs of the system.

8.4. Functional unit

The functional unit (considered for the case studies) is "*1 m² of building skin protecting the building during one year, provided that building and energy production functions are fulfilled during 30 years*".

Based on this functional unit, two (or more) comparison scenarios can be easily defined as the scenario of 1 m² of BIPV system compared to 1 m² of conventional building skin (made with conventional material). After ensuring that the main function is fulfilled, all system differences (in terms of inputs/ outputs) contributes to differentiate the two scenarios. The electric (and possibly thermal) output of the system shall be taken into account on the basis of the energy produced by the system during one year. The corresponding energy including upstream impacts shall be part of the system.

The lifetime of the PV is assumed to be 30 years but different values could be proposed depending on the manufacturer's declaration, on statistical results, or future standards, for example.

8.5. System boundaries of the study

The product studied in this work is a BIPV system. BIPV systems means the module and all the elements enabling its integration in the building and in the energy network. Therefore mounting and flashing (or edging) as well as all electrical connection shall be included. The building is not part of the system. Inverters replacement shall be included based on their lifetime. Any other component of the system with a shorter lifetime shall be included as many times as its replacement.
Concerning waste management, in order to avoid any confusion in terms of recycled and recyclable material, it is proposed that no benefit for recycling or incineration is attributed to the recyclable material at the end of life of the BIPV system. Therefore, only the recycled material entering the system is actually considered (Frischknecht et al. 2016).

8.6. Data needed and possible sources

Modelling environmental performances of the BIPV system requires to collect a dozen of data as a maximum (number is reduced in case of monitoring data for example). Data collection concerns: BIPV category (regarding classification), surface of substituted material, surface of modules, location, tilt, orientation, efficiency (module or cell), performance ratio, packing factor, power inverters, degradation rate and lifetime, substituted material. Experience shown that only with this data which are widely available as specific data or as empirical or statistical data, it is possible to elaborate the Life Cycle assessment of any BIPV system with coherent results. The type of data that can be used for each parameter are presented below:

- BIPV category regarding classification: Observation or manufacturer decision.

- Location: Actual or typical location selected to represent one area.
- Surface of substituted material: BIPV manufacturer information, or statistical data, or observation or architect layouts
- Surface of modules: BIPV manufacturer information or observation or architect layouts
- Tilt: actual data or proxy based on empirical or statistical data for one category of BIPV.
- Orientation: Observation or proxy based on empirical or statistical data.
- Efficiency (module or cell): BIPV manufacturer declaration or default data on the basis of the technology
- Performance ratio: measured data or proxy based on empirical or statistical data.
- Packing factor: Observation or statistical or manufacturer data
- Power inverters: based on project description or estimated from system installed capacity.
- Degradation rate: Empirical value available or statistical data.
- Module Life time: which represents the system lifetime, taken from manufacturer declaration or empirical data or observation
- Substituted material: architect communication, comparison with the rest of the building, or proxy based on empirical or statistical data.

Beyond the system description, the LCI data should be as much as possible based on specific Life Cycle Inventory data. Nevertheless, LCA modelling can be based on generic LCI data (such as ecoinvent) and can use several proxies for activity data such as surface or thickness of flashing material).

If generic Life Cycle Inventory data are used to model the system, ISO requires to ensure the consistency of the data. Using a unit process multi-material database such as ecoinvent guarantee the consistency. With the case study, the approach was proving its flexibility, when few data are available default values and generic background data allowed to assess the carbon footprint, but when more specific data are available more and more accurate results can be obtained.

8.7. Selection of impact categories and characterisation model

The environmental impacts of case studies can be calculated for all existing impact categories. It is recommended to communicate at least the carbon footprint performances but resource mitigation (fossils and minerals) as well as land use or water use are also often communicated. Disregarding the impact categories covered it is preferable to base the assessment on updated and if possible consensual characterization models. For more details on the impact categories that can be used, modellers can refer to the IEA report (Frischknecht et al. 2016).

In terms of communication results, the carbon payback time (CPBT) facilitates results' interpretation. CPBT is the ratio between carbon emissions (generated during BIPV production) and annual carbon reduction of GHG emissions due to the replacement of a conventional system. Results are expressed in years and indicate the time it takes for a BIPV system to compensate the Green House Gas (GHG) emissions released during its production thanks to the replacement of a conventional building skin surface. It allows to put in perspective the immediate release of carbon occurring during the production with time necessary to recover the carbon before starting to save GHG emissions.

9 Conclusions and further works

The first and foremost objective of the work was to investigate BIPV potential environmental assessment. Existing studies, as well as case studies, indicate that ISO 14040-44-compliant Life Cycle Assessment can help reach this goal. Still, the ISO standard applies to a multitude of products and services across the world, so several points must be addressed and carefully framed when putting it into practice with specific products. The "Guide for testers" (elaborated for facilitating case studies' assessment) was extremely useful when defining the functional unit, the scope/system boundaries of the study and the main modelling assumptions. Indeed, BIPV is a vast subject addressing both building-related and renewable-energy-related questions. A great variety of case studies made it possible to correctly lay the foundation of the work. The first outcome is the need for a clear classification enabling the definition of BIPV categories. Beyond this, a great data collection effort allows a detailed environmental assessment of nearly 30 BIPV installations spread across 11 buildings and 9 different countries. A great variety of locations, installations, technologies, mounting solutions, etc. open large opportunities of results interpretations. It allows the definitions of the main LCA rules for BIPV modelling. The scope and the system boundaries of the study and the functional unit are described and the complex (and crucial issue) of multi-functionality in LCA is discussed in depth. The two possible options when addressing multi-functionality (as well as the comparison between BIPV and BAPV) are also investigated and extensively discussed in a dedicated section in the appendix. After having laid down the rules of LCA for BIPV, the minimum parameters and data needs are presented. Default values are also proposed, ensuring that the assessment can be conducted at least at a screening level with minimum data such as location, tilt, exposure, PV technology, BIPV surface and power installed. More detailed data enable more accurate results.

Only climate change is addressed in this report. Even if LCA can apply to all impact categories, it is important to bear in mind that considering only one impact category do not enable to identify the potential transfer of impacts from one impact category to another. A multicriteria assessment covering a broad range of impact categories would better reflect the environmental consequences of the installation of BIPV.

The main results observed can be summarized as follows: 1) Environmental performance shall be addressed at-the-system level and not at-the-module level, even if this requires to make pre-installation assumptions; 2) BIPV carbon footprint can be lowered by means of design optimization or green electricity consumption during the modules production stage; 3) The highest differences in environmental performances between scenarios with or without BIPV are observed when BIPV is connected to an electricity network with a high carbon footprint per kWh. 4) Environmental assessment (and particularly the carbon footprint including the use phase) is important even at the early BIPV design stage (way before its installation on a building).

The analysis of the case studies at world level shows that BIPV installations are not optimum for energy production, are technically complex and represents big investment. An important motivation of building owners is their environmental awareness but green washing and misleading declaration is

often weakening environmental communication. Elaborating a reliable and consensual environmental assessment framework is a positive response to mistrust. The two conditions of success of such an effort are (1) elaborating rules allowing comparative assessment in coherence with environmental reality of the product and with existing international framework; (2) ensuring that the proposed method is easy to use with limited expertise and time requirements. The work achieved in T15 STD demonstrate that these two requirements can be fulfilled with simple rules that fully respect the international framework of Life Cycle Assessment. For that purpose, the rules are applied to 11 case study that are very different.
The work done also fully fit with the meaning of ISO 14040-44 which is stated in its introduction : "LCA can assist in (1) identifying opportunities to improve the environmental performance of products at various points in their life cycle, (2) informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign), ...(3) marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration)."

Further improvements can still be done especially regarding the categories covered and the quality of the default values of parameters. While only three categories are covered in the work, it is possible to explore more case studies in order to address more categories. Also a number of parameters are used based on empirical data. Even if these data are the only one available, they are rather old and could be updated with statistical data. It is the case for the performance ratio in order to get accurate statistical data at the category level. It is also the case for the degradation factor where only one value is used for all cases whereas several publications indicate that the degradation factor vary with the PV technology. Also, defining a reference location for each country (as what was done for the office building for example) would facilitate modelling of BIPV in all situations, even when its future location is not yet defined (for eco-design or prospective assessment of BIPV). The lifetime of BIPV can be further discussed since it is a parameter which has a big influence on the results. In terms of life cycle inventory, current case studies are strongly depending on ecoinvent. Developing more datasets elaborated as unit processes would strongly help getting more accuracy and transparency in the studies. This is especially the case for mounting systems, edging, flashing, connection and regulation system for the grid connection, and also hybrid modules.
The question of reparability, reuse, and recycling in a circular economy perspective was not at all address in the current work and can be further explored. At the same time, the issue of critical resources and resource depletion are offering promising research perspectives and should be now addressed.

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Annex : Detailed unit process data for LCA modelling

Detailed unit processes are made available with XL table -

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