



BIPV boost

Parametrization, optimization and automation during design stage in order to optimize the BIPV cost-to-power ratio

BIPVBOOST

“Bringing down costs of BIPV multifunctional solutions and processes along the value chain, enabling widespread nZEBs implementation”

Start date: Month Year. Duration: 4 Years

Summary

This document describes a first prototype designed to extend the BIMsolar® [1] software in order to optimize the end-user cost of the system and the electricity cost in the long term. This first approach deals with simulation process and an optimization process. The simulation is based on a virtual model in the form of the BIMsolar® software and a Python script. The goal is to build a first prototype of the simulation and optimization in order to show the capabilities of such an optimization process. In a later stage, during the BIPVBOOST project, this optimization prototype will be transformed into an industrial tool and will be integrated into the BIMsolar® software.

This python script is able to read a file containing the production figures of BIPV layouts provided by the BIMsolar® software developed by ENERBIM. From these production data and another file containing load profile data, the simulation model is able to compute the difference between production and load per hour of the year. The test case of a residential house with self-consumption strategy and storage with batteries was selected. This difference is then used to carry out the charging and discharging process of the battery. The remaining amount of electricity will then be used to develop the electricity cost model over a number of years that corresponds to the first objective to minimize. A set up cost model is also developed in the simulation model and corresponds to the second objective to be minimized.

The optimization process is performed by the XTREME [7] software developed by Optimal Computing, based on PARETO frontier methodologies. The optimizer actually searches for a number of design variables in order to obtain the most optimized solutions, i.e. those where both objectives are minimized. To do this, the optimizer will vary two types of variables. The first type of design variable is the number of BIPV modules on the building surfaces. The second type of design variable is the maximum capacity of the battery. The optimization software will therefore vary these design variables from 0 to their maximum in order to find the combinations that will give the most optimized results.

An existing residential house project was selected from the cases already available and provided by BIMsolar®. The results obtained after optimization show that this first prototype is rather reliable since the results obtained seem consistent. Once analysed, they allow to identify the parts of the simulation model that need to be improved and the assumptions that need to be raised in order to obtain a simulation model as close as possible to reality.

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1 EXECUTIVE SUMMARY

1.1 Description of the deliverable content and purpose

This document describes a first optimization prototype designed to be added to the BIMsolar® [1] software. The goal of this optimizer is to achieve BIPV cost optimization, by performing a multi-objective optimization of both the BIPV end-user cost and the electricity cost over a period of time.

First, this document contains an introduction describing the main hypotheses and objectives of this first prototype. Then the methodology used is presented and divided into two parts: the simulation process and the optimization process. The building selected to test this first prototype is also presented. The simulation model describing the necessary input files, the cost models used and other assumptions are presented. A summary table containing all the constant values, formulas and assumptions is then produced in the following section. Finally, the results of the optimization of the first test case are presented and analyzed. A sensitivity analysis was carried out to study the influence of some cost parameters such as the total cost of a BIPV installation or the cost of energy. These will highlight the objectives of reducing the cost of BIPV solutions to be achieved.

Finally, the document is concluded with a brief discussion to identify the main observations made after this first prototype and the points for improvement for the rest of the project.

1.2 Relation with other activities in the project

Table 1-1 depicts the main links of this deliverable to other activities (work packages, tasks, deliverables, etc.) within PVSITES project. The table should be considered along with the current document for further understanding of the deliverable contents and purpose.

Table 1-1 Relation between current deliverable and other activities in the project

Project activity	Relation with current deliverable
D1.1	Data on valuation of the end-user cost of different reference cases

1.3 Reference material

Not applicable.

1.4 Abbreviation list

EB – Educational building

BIPV – Building Integrated Photovoltaics

SFH – Single-family house

2 INTRODUCTION

This report presents a first prototype to extend the existing BIMsolar® [1] software to optimize the cost of BIPV setup based on a virtual model. The goal is to provide a tool that would help architects and BIPV designers.

For this purpose, the simulation and optimization processes are first presented. The simulation process involves the use of the BIMsolar® software developed by ENERBIM and the XTREME [7] software (optimizer) developed by Optimal Computing. A first cost model simulation in the form of a Python script was developed and is presented in this report. All simplifying assumptions are presented. The simulation model is then detailed, including a description of the different cost components used as well as the constant values chosen.

In order to demonstrate the principle and efficiency of this procedure, a first test case is evaluated and presented in this report. The results were analysed and allowed to identify the parts of the simulation model that require improvement.

This first step allowed the consortium to carry out a first approach to the problem in order to identify the items to be modified and the hypotheses to be raised, the aim being that the simulation model should provide the results as close to reality as possible and, therefore, as reliable as possible.

3 METHODOLOGY

This numerical optimization procedure is based on a simulation process to compute the electricity production and the cost, and an optimization process to search for the best possible BIPV setup. As a starting point, the simulation and optimization processes are presented. Figure 3-1 shows the method used and is further described and explained in the following sections.

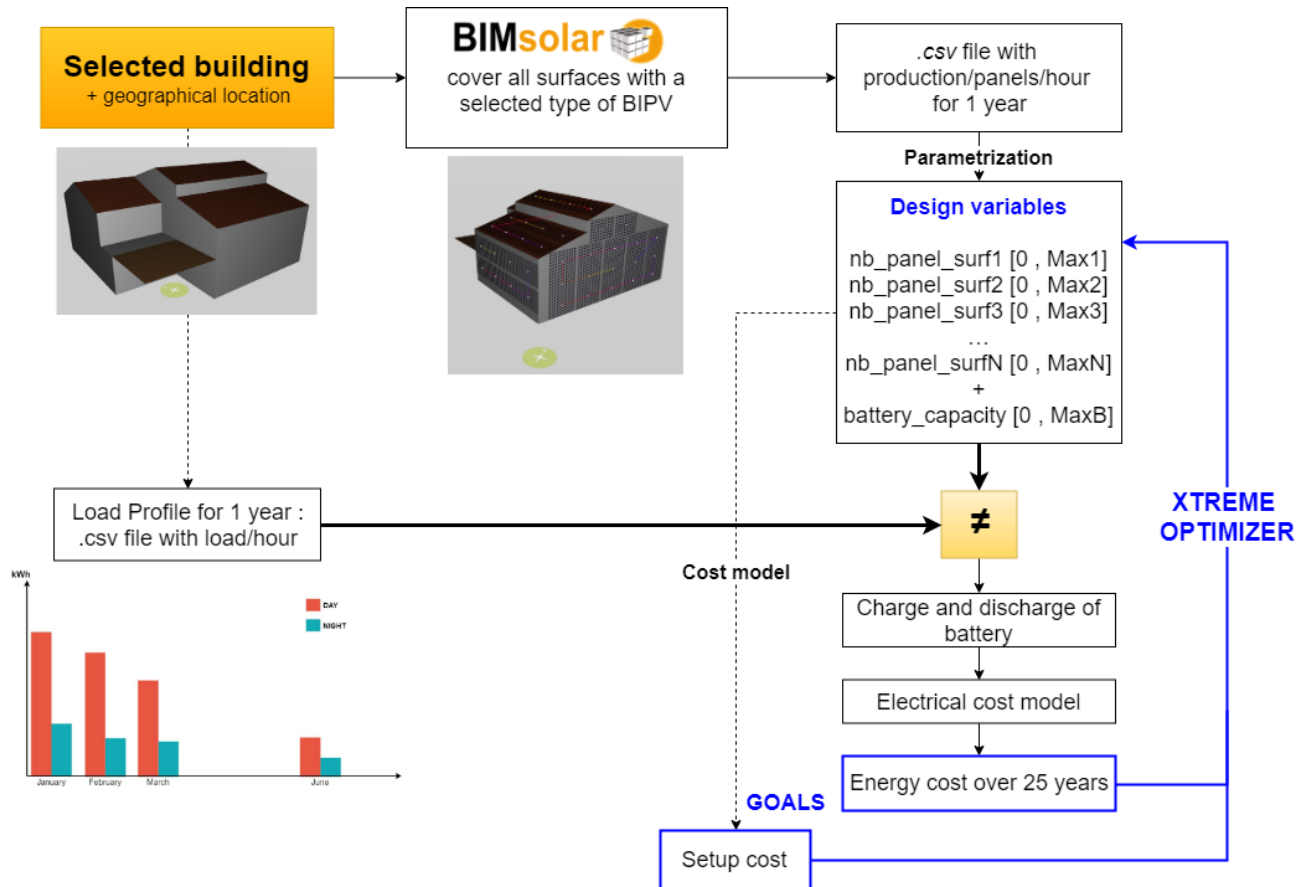


Figure 3-1 : Diagram of the optimization process

3.1 The simulation process

To illustrate and develop this first prototype, an existing building from the BIMsolar® [1] database was selected. The simulation process is composed of 3 main blocks: the BIMsolar® software, the load profile and the cost model. These 3 blocks are launched using a Python script to automate the simulation process. The cost model is also written inside the python script for this first prototype.

3.1.1 BIMsolar®

All building surfaces can be filled with a maximum number of photovoltaic modules. In this project, Building Integrated Photovoltaics (BIPV) are preferred. Once all surfaces have been covered with modules, it is possible to choose the inverter(s) and wiring of the installation. Then, the BIMsolar® software allows to calculate the electricity production by surfaces. A .csv file is exported from BIMsolar® software, containing the electricity production for every hour and for each surface for a period of 1 year.

From the selected building, it is also possible to obtain a load profile. For the first test case, a load profile provided as an excel file was used. This file was sent to us directly by email and probably comes from *CREST Demand Model* [2] but without certainty. It makes possible to produce the first prototype but will have to be changed for the rest of the project. The Python script therefore uses a .csv file that contains the building's load request per hour over a one-year period. Once the two .csv files (production and load) are recovered, the Python script calculates the difference per hour of the year between the electricity production from the BIPV installation and the load profile of the building.

This difference is then used in the part of the script about charging and discharging the battery. Figure 3-2 helps to understand how it works. If the difference between the load and the production is positive, it means that more electricity is consumed than is produced by the modules instantly. In this case, if the battery is not empty, the stored electricity can be recovered, and the battery is discharged. However, if the battery is empty, the electricity required for consumption is taken directly from the public grid. On the other hand, if the difference between the load and the production is negative, it means that not all the electricity produced by the modules is consumed instantly. Therefore, if the battery is full or not is verified. If it is filled, the excess electricity is then returned to the public grid and if the battery is not at its maximum capacity, the excess electricity is used to charge the battery.

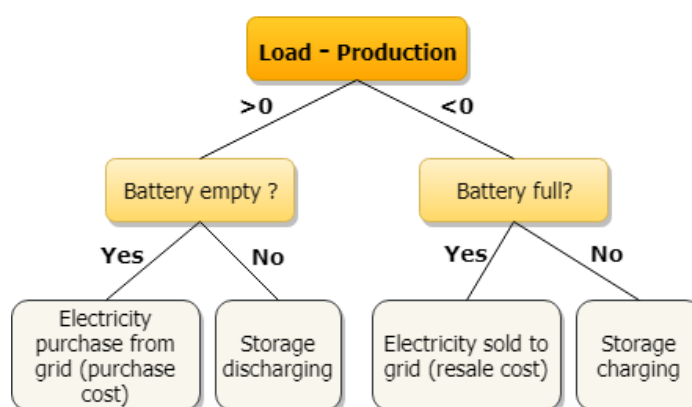


Figure 3-2 : Battery charging and discharging process

From a cost model using purchase and resale prices of electricity at different times of the day, it is possible to calculate the amount of the electricity bill over 1 year. For the first simulation model, the hypothesis of using a constant real value for the cost of retail electricity was assumed. Later, a factor of variation in the price of electricity will be applied. However, this is not a linear and constant variation in electricity prices, but a random variation. For this purpose, in deliverable D1.1 [3], they apply a normal distribution law to perform the various analyses. The same law will probably be applied to the next simulation model in order to obtain more realistic results. In this report, only the inflation rate will be applied to each cost calculated over the long term.

Therefore considering the inflation rate, the calculation of the cost of electricity over 25 years can easily be determined. This cost corresponds to the **first objective** that will be minimized with XTREME [7]. The hypothesis of 25 years is taken following the base case value taken in the D1.2.

The **second objective** to be minimized is the send-user cost of the BIPV system. To determine this, a cost model was created in the script. It therefore allows to calculate the financial investment of the installation from the number of modules chosen per surface taking into account the type of surface as well as the capacity of the battery chosen.

The **design variables** are therefore the number of modules on each surface of the building. These parameters can therefore vary from 0 (no module on the surface) to MaxN (the surface is completely filled with modules). Another type of parameter has been added. This is the charging capacity of the battery. This additional design variable can therefore vary from 0 (no battery) to MaxB (the maximum battery capacity). These variables and their range of variation will be presented later.

To be able to use the data from this production file and perform the following steps, a Python script has been created. It is therefore this script that will be called by the **XTREME** optimization software [7]. The python script performs the following steps:

1. The first step of this script is to read the design variables.
2. Apply the design variables to the csv file of the electricity production provided by the initial BIMsolar® software
3. Read the load profile
4. Subtract for every hour the load profile from the production profile
5. Apply the battery and cost models to the excess or missing electricity per hour

3.2 Optimization process

The principle of the XTREME optimization software is therefore to give different values to the design variables in order to minimize the two objectives: the setup cost and the energy cost over 25 years. It is therefore a **Multi-Objective Optimization** that provides the best combinations of variables in the form of a Pareto front.

The Pareto front gathers all the Pareto optimal solutions. Figure 3-3 explains this principle. In this example, the aim is to minimize $f1$ and $f2$. For this purpose, several solutions are computed and the points are graphically represented according to $f1$ and $f2$. Since the optimal points are those when $f1$ and $f2$ are the smallest possible, it is easy to understand that:

- B is a Pareto point because it is not possible to find a point having both $f1$ and $f2$ values better than the B point.
- C is not a Pareto point because the point B has both a better value for $f1$ and $f2$.

Therefore, the Pareto front will be the curve passing through the lowest and leftmost points in the graph.

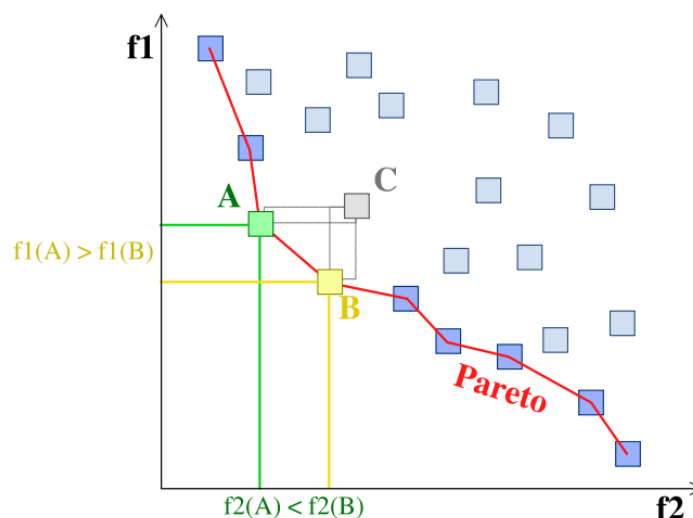


Figure 3-3 : Example of Pareto front [4]

4 TEST CASE AND ASSUMPTIONS

In order to develop the procedure and demonstrate the performance of the first prototype procedure, a test case was selected and is further described hereafter.

4.1 Test case description

For the first test case, the **residential building** shown in Figure 4-1 was used. The geographical location chosen for the solar radiation is the city of **Brussels in Belgium**. This figure also shows the orientation of the building and its exposure to the sun during the day. The six building surfaces chosen to be potentially covered with modules are shown in Figure 4-2. The maximum number of panels per surface is also indicated.

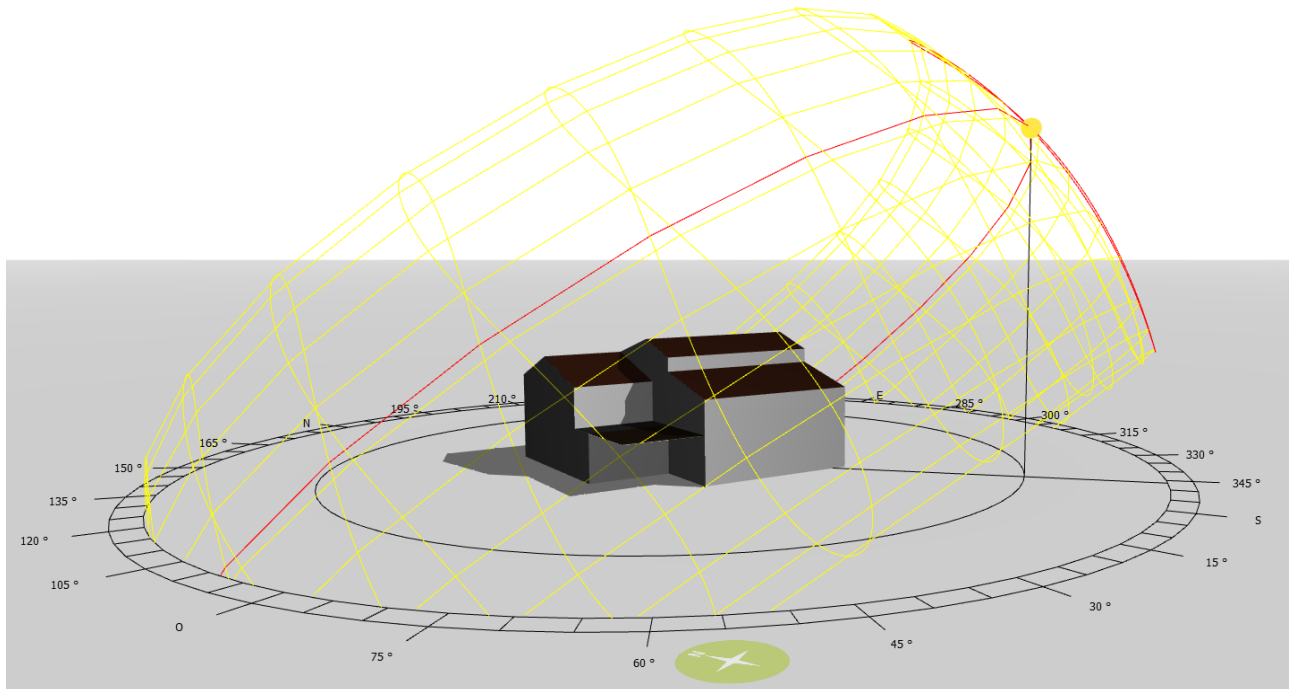


Figure 4-1 : Selected building

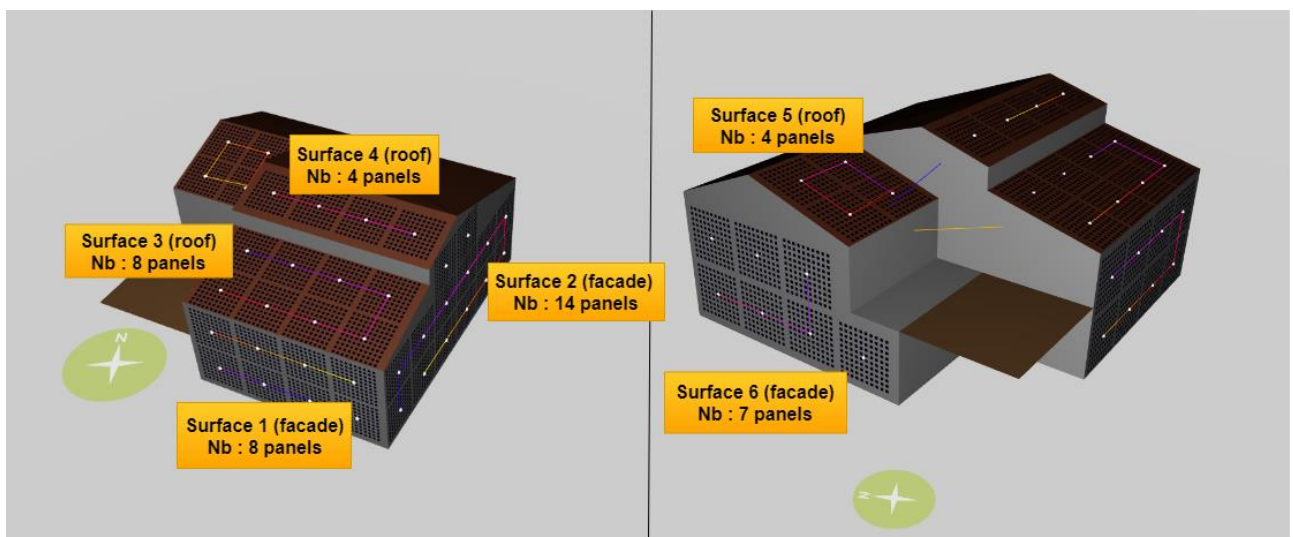


Figure 4-2 : Surfaces and maximum number of modules

The list of surfaces, their characteristics and maximum number of panels are summarized hereafter:

- Surface 1: south-west facing façade with a maximum of 8 modules
- Surface 2: south-east facing façade with a maximum of 14 modules
- Surface 3: roofing with a maximum of 8 modules
- Surface 4: roofing with a maximum of 4 modules
- Surface 5: roofing with a maximum of 4 modules
- Surface 6: façade facing northwest with a maximum of 7 modules

Figure 3-3 and Figure 4-4 show the average annual irradiance and shading on the building respectively. It can be noted that on surfaces 3 and 5 (roof surfaces), the irradiance is lower in some areas due to the presence of shading. These shades cause a loss of irradiance and therefore a loss of electricity production of the concerned modules.

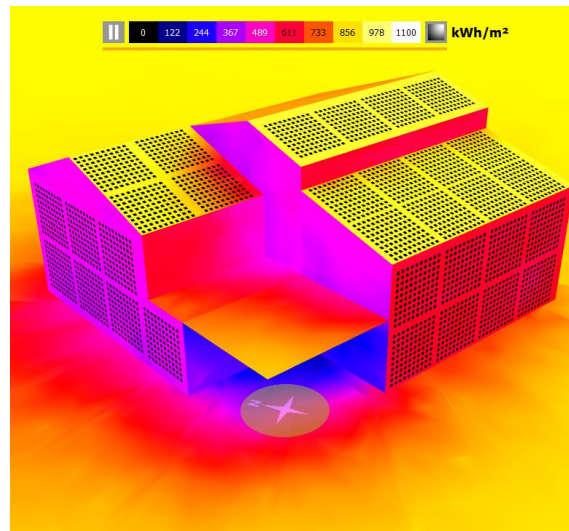


Figure 4-3 : Yearly irradiance

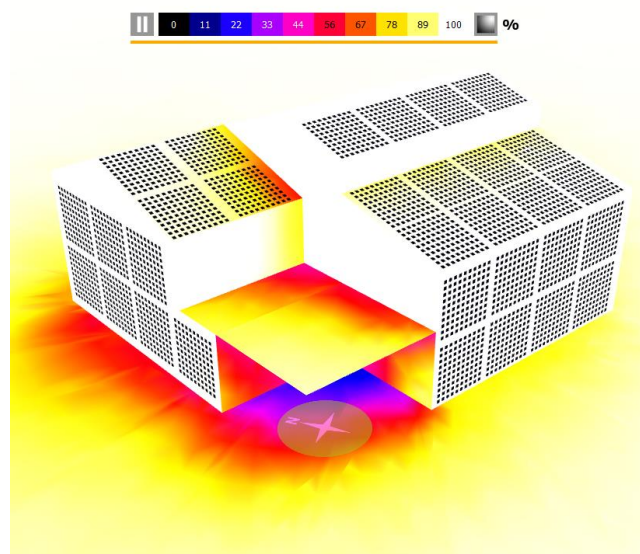


Figure 4-4 : Shading

4.2 First assumptions

The **first assumption** that has been made is that all the panels placed on the surfaces of the building are the same. The BIPV module has been selected in such a way that the peak production is around the average value of 300 Wp/module. In addition, the panels with the smallest dimensions have been selected in order to be able to place as many of them as possible on a surface and therefore to have the widest possible range of variation of design variables. The characteristics of the BIPV type selected for the entire installation are shown in Figure 4-5.

Supplier:	Standard
Model:	Mono 125 - Pseudo 2bb
Technology:	mono_Si
Peak power:	300 Wp
Size:	2250x2250 mm
Cells:	10x10 (100)
Diodes:	1
NOCT:	45.0 °C
Voc:	65.4 V
Vmpp:	55.0 V
Isc:	5.9 A
Bendable:	No

Figure 4-5 : Characteristics of the selected BIPV type

The **second assumption** is to consider that all panels of the same surface produce the same amount of electricity. Since the production file obtained from BIMsolar® [\[1\]](#) allows to know the production of electricity per surface, this assumption was made in order to be able to calculate the exact production of a surface according to the number of modules it actually contains (number of modules chosen by the optimization software). Therefore, another simplification that was made at the beginning of the project is not to consider the shading losses caused by some modules.

Finally, a **last hypothesis** is the use of automatic inverters and wiring. Indeed, after having placed the modules on the building with BIMsolar®, it is necessary to select the inverter(s) and the wiring. If this is not done, it is not possible to get the production file.

4.3 Assumption raised

After some tests with these first assumptions, the aim was to remove some of them. The most important one seems to be the one concerning shading. Indeed, the modules being placed under a shaded area will produce less electricity than fully irradiated modules.

If all modules are connected to a single central inverter, shadows drastically reduce production. Indeed, if a module is shaded, an electricity loss occurs and since the modules are connected in series, the total electricity produced drops drastically. To solve this problem, micro inverters can be used. Each micro-inverter is connected to 1 or 2 modules, which means that the production of the entire installation is not affected if one module is shaded. There are also optimizers that are added to the central inverter and allow only the shaded module to be disabled. Since in the BIMsolar® software, production is only reduced in the case of shading on a module and not cancelled, it will be assumed that micro-inverters are connected to the modules. The assumption of using micro inverters has therefore been made. It has been assumed a lifetime of 25 years for the micro inverter. This hypothesis will be checked in the final version of the task. Therefore, since the simulation period is 25 years, the replacement of micro inverters is not taken into account in this first simulation model.

As a result, it is now necessary to consider production losses due to shading. For these, since the use of micro inverters is considered, the production of shaded panels must be cancelled. First of all, it is necessary to identify the shaded areas. As explained above, surfaces 3 and 5 (roof) are sometimes shaded. As a result, these surfaces have been **divided into 2 sub-surfaces** as shown in the Figure 4-6. Surfaces 31 and 51 are therefore the surfaces without shadows while surfaces 32 and 52 are the surfaces with shadows. Once the change of the studied surfaces is realized, the Python script is able to drastically reduce the production of shaded panels. Indeed, in the production file provided by BIMsolar® [1], each column corresponds to the production per hour of a surface (or sub-surface). The Python script is therefore able to see if there is a difference of production between the column corresponding to the sub-surfaces that are not shaded and the column corresponding to the shaded one. If there is a difference between the hourly values, it means that one of the sub-surfaces is instantly shaded. As a result, the script applies an 80% reduction in its electricity production. Indeed, in reality, if a panel is shaded, it produces almost no electricity. The 80 % decrease rate was chosen to consider that there is still a small amount of electricity produced by diffuse radiation.

This change therefore allows to calculate the production of sub-surfaces separately. The XTREME optimization software [7] can vary the number of modules on each sub-surface. The list of considered surfaces is therefore adapted to the following list:

- Surface 1: south-west facing façade with a maximum of 8 modules
- Surface 2: south-east facing façade with a maximum of 14 modules
- Surface 31: roofing without shading with a maximum of 4 modules
- Surface 32: roofing with shading with a maximum of 4 modules
- Surface 4: roofing with a maximum of 4 modules
- Surface 51: roofing without shading with a maximum of 2 modules
- Surface 52: roofing with shading with a maximum of 2 modules
- Surface 6: façade facing northwest with a maximum of 7 modules

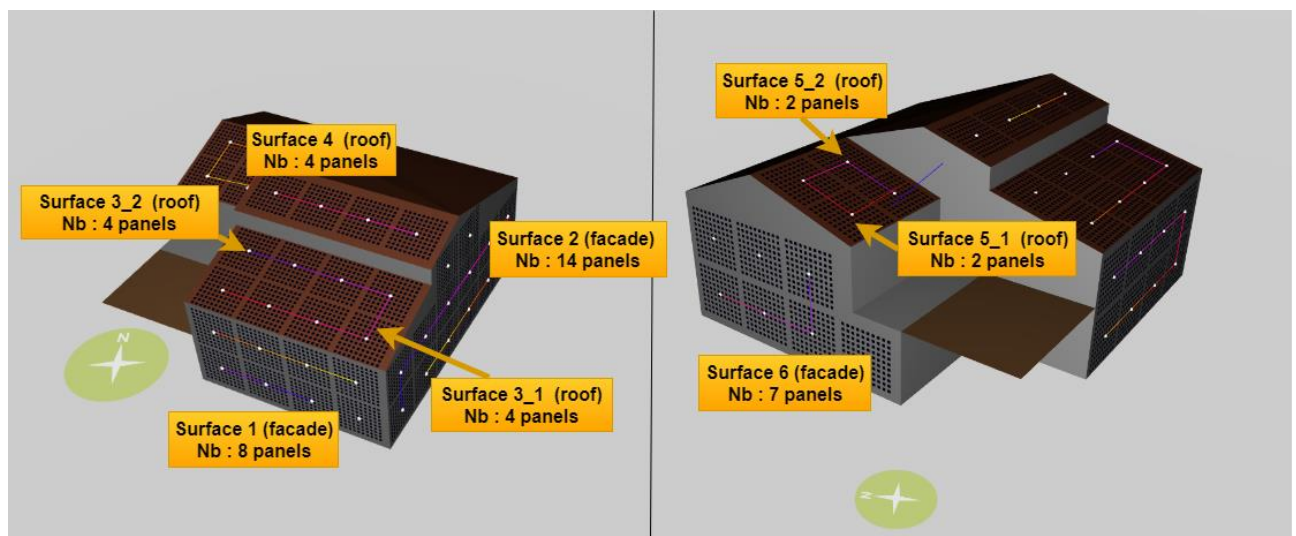


Figure 4-6 : New surfaces (taking into account shading)

5 SIMULATION MODEL

In this part of the report, each specificity of the simulation model will be explained. First, the inputs and outputs of the Python script will be detailed as well as the files necessary for the simulation. Then, the assumptions made for each part of the simulation will be presented. The electricity cost model and the setup cost model will then be explained, specifying the constant values.

5.1 Inputs and outputs

For the test case presented previously, there are nine input variables. Eight of them correspond to the number of modules per surface while the last one corresponds to the charging capacity of the battery. All design variables have the following variation range: [0.1] with 1 being the maximum number. For the variables corresponding to the number of modules per surface, the maximum 1 is therefore the maximum number of modules that can be placed on each surface and for the battery, it corresponds to the maximum charging capacity of the battery in kWh. The maximum numbers of each input variable are listed in Table 5-1. The maximum values for the surfaces therefore refer to the Figure 4-6, while the maximum value of the battery capacity was taken arbitrarily.

Table 5-1 : Maximum number of input variables

Input/Design variables	Maximum
X1	8
X2	14
X31	4
X32 (shading)	4
X4	4
X51	2
X52 (shading)	2
X6	7
X7 (battery)	100 kWh

The output variables of the simulation are **variables F1 (electricity cost over 25 years) and F2 (setup cost)** which are minimized during optimization and which allow to obtain a Pareto front when the evolution of F2 as a function of F1 is observed.

The setup cost includes the end-user cost of the BIPV system as well as the cost of the first battery (if there is one). On the other hand, the cost of electricity over 25 years considers the electricity bill over 25 years but also the cost of possible replacement components (batteries, inverters, etc.).

5.2 Files required for simulation

To be able to start the simulation, two .csv files are required. The first file is the one that comes from the BIMsolar® software and contains the production per hour for each surface (and sub-surfaces) for 1 year. This

file therefore provides the electricity production of the installation when the maximum number of modules is placed on each surface.

The second necessary file is the one containing the building's load profile. For this purpose, an Excel data file containing load profiles from several cities in Portugal was used to make the first prototype. As these load profiles are referred to a larger building, an arbitrary scaling is applied to have a total yearly consumption closer to a typical residential house in Belgium. In this case, a scale factor is applied to obtain a consumption of 10 000 kWh/year which is an average electricity consumption of Belgian households (2 adults, 2 kids) that uses electrified devices for space heating and water heating. In the case of this simulation model, an average of 3500kWh/year was therefore considered for the consumption of electricity for the lighting and appliances, an average consumption of 1500kWh/year for hot water in a domestic context and a consumption of 5000kWh/year for heating the building. In the file containing the load profile, data for each of these consumptions are included. After summing all these consumptions, a .csv file was created, containing the average consumption per hour of a day for each month of the year. In addition, the consumption of weekdays and weekend days is represented. The structure of this file is shown in Figure 5-1. In the future, this file containing the load profile will have to be improved in order to be adapted as best as possible to the building studied and its geographical location.

Finally, on Figure 5-2 the total production as well as the consumption per month over a period of one year can be observed. For the total production, the building is considered equipped with the maximum number of panels.

kWh		0h to 1h	1h to 2h	2h to 3h	...	23h to 24h
January	week	0.0867257	0.0867257	0.086725714	...	1.7573654
February	week	0.0867257	0.0867257	0.086725714	...	1.2526313
March	week	0.0867257	0.0867257	0.086725714	...	0.6239532
...	week	...	...	...	...	...
December	week	0.0867257	0.0867257	0.086725714	...	1.2595563
January	weekend	0.0867257	0.0867257	0.086725714	...	1.7424309
February	weekend	0.0867257	0.0867257	0.086725714	...	1.6733076
March	weekend	0.0867257	0.0867257	0.086725714	...	0.7551425
...	weekend	...	...	...	...	...
December	weekend	0.0867257	0.0867257	0.086725714	...	1.4228269

Figure 5-1 : Structure of load file

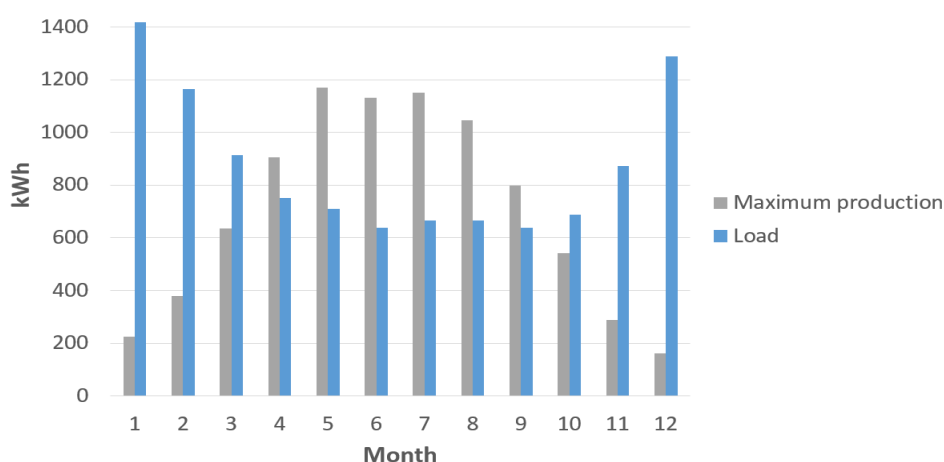


Figure 5-2 : Comparison of production and load profile

5.3 Electricity cost model

Once the .csv files are processed and used to realize the difference between load and production for each hour of the year, the battery charging and discharging process (as explained in Section 3.1) is performed. After that, the electricity cost model must be developed. In this section, data on feed-in tariffs and resale of electricity to the public grid are required.

For this test case, the tariffs on ENGIE Electrabel's Belgian electricity bill for 2017-2018 were used. The different rates per kWh and fixed charges per year are shown in Figure 5-3. As it can be seen in this table, two final tariffs are used: the peak consumption tariff (applied from 6 AM to 10 PM) and the off-peak consumption tariff (applied from 10 PM to 6 AM and at weekends). In the case where the production of BIPV modules is too large and not fully consumed, the simulation model first checks whether the battery can be recharged with this excess electricity. If there is still a surplus of electricity, it is injected into the grid. The price of electricity sent to the grid varies according to countries and situations. For this simulation model, the assumption of taking a resale price of 5 €/kWh was assumed. In addition, it is considered that there is no VAT on the resale price of excess electricity.

	Rate	Unity	VAT	Price including VAT
Energy				
Fixed fee	22.6	€/year	0.21	27.346
Peak consumption	0.0536339	€/kWh	0.21	0.064897019
Off-peak consumption	0.0440189	€/kWh	0.21	0.053262869
Green energy costs				
Green energy costs	0.024093161	€/kWh	0.21	0.029152725
Network costs				
Distribution costs	0.0734713	€/kWh	0.21	0.088900273
Transportation costs	0.0323988	€/kWh	0.21	0.039202548
Royalties				
Energy contribution	0.001926	€/kWh	0.21	0.00233046
Federal contribution	0.0034111	€/kWh	0	0.0034111
Connection fee	0.00075	€/kWh	0	0.00075
Total cost peak hours	0.1655911	€/kWh		0.228644125
Total cost off-peak hours	0.1559761	€/kWh		0.217009975

Figure 5-3 : Electricity purchase rates (ENGIE Electrabel 2017-2018) [5]

To be able to change these constants more easily in the script, a .csv file containing these data has been created. As a result, depending on the country, the electricity feed-in tariff can easily be modified without requiring any script modification.

Finally, after calculating the electricity bill over one year, the total cost of retail electricity over 25 years remains to be calculated. To do this, the inflation rate must be considered and the value of 1.5% was taken in reference to deliverable D1.1 [3]. This inflation rate is applied to all long-term expenses, i.e. the electricity bill over 25 years, which is here assumed to remain constant in real terms, but also the components to be replaced (e.g. battery).

5.4 Setup cost model

The setup cost is composed of the 2 terms:

- The total cost of installing the BIPV modules which will be called BIPV end-user cost (containing materials, installation, transport, administrative and legal costs, inverter (the first one installed) and electrical setup) and,
- The cost of the battery

The first step is to determine the unitary end-user cost of a BIPV module.

5.4.1 BIPV end-user cost

From the design variables that will be chosen by the optimizer, it will be possible to determine the setup cost of the installation. As a reminder, the design variables are the number of modules per surface and the maximum capacity of the battery.

The price of a BIPV roof is different than the price for a BIPV façade (see D1.1). As a result, two different cost functions are used, one for BIPV roof systems and one for BIPV facade systems.

The price per m² chosen is based on a cost analysis present in the deliverable D1.1[3] carried out on several reference cases. For the application of BIPV roof, the total end-user cost of the *SFH_c* reference case was applied. This case corresponds to a single family house with CIGS (Copper Indium Gallium Selenide) photovoltaic technology. For this reference case, the total end-user cost is 249 €/m². To be consistent, a reference case with the same type of technology was chosen for the case of a facade application. The reference case *EB_b* (educational building) has been selected. For the application of the modules on the facade, the following total end-user cost will be used: 412 €/m².

In addition, in order to get closer to reality, a price variation factor was applied according to the size of the installation. To do this, a decreasing logarithmic function was chosen. The price actually decreases with more modules in the installation and the number of modules can be represented by the total peak power of the installation in kWp. Figure 5-4 and Figure 5-5 therefore allow to visualize these decreasing unit price curves (€/m²) as a function of the total peak power. Logarithmic functions were therefore applied in the simulation model.

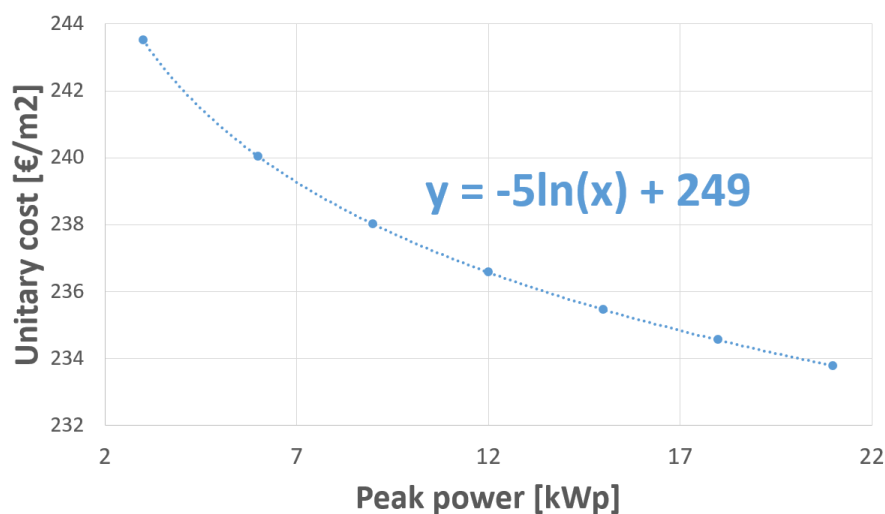


Figure 5-4 : Unitary cost of BIPV roof module

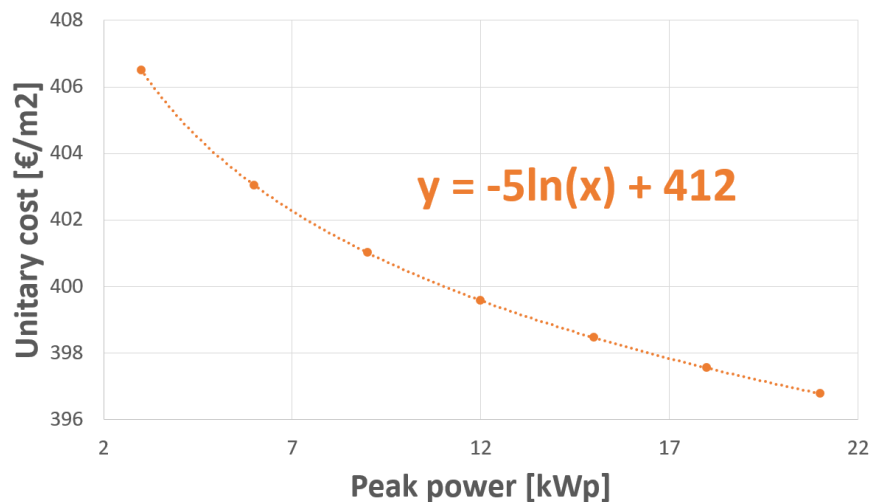


Figure 5-5 : Unitary cost of BIPV facade module

For the first prototype, the peak power of the BIPV module type chosen is 300 Wp.

Then, an initial cost model is imposed when installing a module on a surface. Indeed, this cost allows to make the optimizer understand that it is more interesting to fill an entire surface before filling another one. This cost could correspond, for example, to the cost of installing the scaffolding if the filled surface is at roof level. In the case of several roof surfaces, it may be more interesting to place 4 modules on one surface rather than placing 2 panels on one surface and having to move the scaffolding to place 2 modules on another surface. The initial cost currently has an arbitrary value of 500€ per surface containing at least one module. This constant value can of course be modified depending on the installation.

Finally, the photovoltaic VAT rate applied to the installation is the classic rate of 21% in this case. In the Python script, the VAT parameter applied to the BIPV cost is a constant that can be easily modified according to the test case.

5.4.2 Battery cost

After the development of the cost model for BIPV layouts, the next step is to develop the one for the batteries. As a reminder, the optimizer will be responsible for tuning the battery capacity from 0 to 100kWh.

The first hypothesis that has been made is to choose a lithium-ion battery. This choice was made because this type of battery has better performance than the others. Although lithium-ion batteries are more expensive, they have a much longer life (and therefore a much higher maximum number of cycles), making them the most cost-effective type of battery. In general, this type of battery reaches about 2000-2500 cycles with a maximum discharge at 80-90% of its capacity. Anyway, for any type of battery, deep discharges cause a decrease in battery life. For the first simulation, the battery can therefore perform 2200 cycles with a maximum discharge of 80%.

Then, it is necessary to find a function that gives the cost of the battery according to its charging capacity. As a first estimate, a linear function was used with 800€/kWh. However, the price was increasing very quickly. In order to get closer to reality, the prices of the lithium-ion batteries sold by the supplier *wattuned* [6] were used as well as the capacity of each battery. The prices recovered on this site are prices with VAT included. These data are plotted on a graph to compare the evolution of the unit price (€/kWh) and the battery capacity (kWh). Figure 5-6 shows the different points and the trend curve passing through this point cloud. The function of this curve, shown in Figure 5-6 was therefore used to evaluate the price of the battery according to its capacity.

To improve the battery cost model, an initial cost will also be chosen. To begin with, this cost will be 200€, which is a value that is taken arbitrarily and can be modified later. This initial cost corresponds to the cost of the regulator. In fact, the regulator is a device connected to the battery that controls the charging and discharging of the battery. As a result, the regulator can limit the discharge of the battery to 80% in order not to damage its life in the event of a deep discharge.

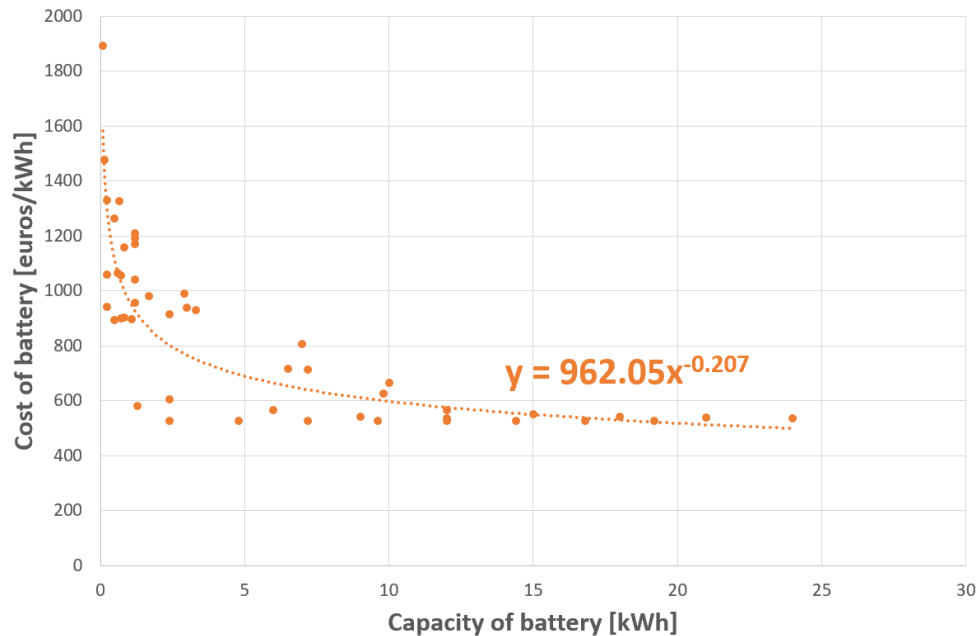


Figure 5-6 : Battery cost in function of capacity

Finally, since the battery does not have a life span as long as solar panels, it will probably have to be replaced over the 25-year period. To enable this feature, the script is able to calculate the number of charging cycles of the battery and compare it with the maximum number of cycles required (2200 cycles) and thus predict the number of batteries required over 25 years. The price of the additional batteries is then calculated considering several rates of variation. First, as with other long-term expenditures, the inflation rate of 1.5% was applied. This is therefore a rate that takes into account the increase in price over the years. However, the price of batteries will decrease in the coming years. A battery price reduction rate of 1.5% is therefore applied. The cost of the additional battery(s) is therefore added to the energy cost over 25 years (which corresponds to objective F1 to be minimized).

6 SUMMARY OF VALUES TAKEN FOR THE ENTIRE SIMULATION

Before moving on to the optimization results, this section summarizes all the important terms, constant, laws used in the simulation model.

Table 6-1 allows to visualize all the constant values, formulas, variables and their variation range used during the simulation

Table 6-1 : Summary of data used for simulation

Data	Unit	Value	Description
Life time	years	25	<ul style="list-style-type: none"> Period over which the simulation is performed Estimated life time of BIPV modules and micro inverters
Inflation rate	%	1.5	Applied to all expenses over the long term
VAT	%	21	Applied to BIPV end-user cost and prices of retail electricity
Input variables			
X1	/	[0, max1], max1 = 8	Number of module on surface 1 (south-west facing façade)
X2	/	[0, max2], max2 = 14	Number of module on surface 2 (south-east facing façade)
X31	/	[0, max31], max31 = 4	Number of module on sub-surface 31 (roofing without shading)
X32	/	[0, max32], max32 = 4	Number of module on sub-surface 32 (roofing with shading)
X4	/	[0, max4], max4 = 4	Number of module on surface 4 (roofing)
X51	/	[0, max51], max51 = 2	Number of module on sub-surface 51 (roofing without shading)
X52	/	[0, max52], max52 = 2	Number of module on sub-surface 52 (roofing with shading)
X6	/	[0, max6], max6 = 7	Number of module on surface 6 (façade facing northwest)
Xbattery	kWh	[0, maxB], maxB = 100	Maximum battery capacity
Output variables			
F1	€	/	Electricity cost over 25 years

F2	€	/	Setup cost
BIPV selected			
(Standard – Mono 125 – Pseudo 2bb, mono_Si)			
Peak power	Wp	300	Peak power of 1 module
Size	m ²	2.25*2.25 = 5.0625	Size of 1 module
Prod. reduction rate	%	80	Applied to sub-surfaces shaded
Average electricity consumption	kWh/y	10 000	Reference value chosen to scale the load profile file
Electricity cost model			
(assumed to remain constant in real terms)			
Fixed fee (VAT excl.)	€/y	22.6	Fixed fee to be paid each year
Total cost peak hours (VAT excl.)	€/kWh	0.1655911	Applied from 6 AM to 10 PM
Total cost off-peak hours (VAT excl.)	€/kWh	0.1559761	Applied from 10 PM to 6 AM and at weekends
Resale price	€/kWh	0.05	Electricity injected to the grid (no VAT applied)
BIPV end-user cost			
Initial price of BIPV roof module	€/ m ²	249	Price to which is added a reduction according to the size of the system
Logarithmic function of BIPV roof cost	€/ m ²	$y = -5\ln(x) + 249$	$y = \text{cost of BIPV system [€/ m}^2\text{]}$ $x = \text{peak power of the system [kWp]}$
Initial price of BIPV facade module	€/ m ²	412	Price to which is added a reduction according to the size of the system
Logarithmic function of BIPV facade cost	€/ m ²	$y = -5\ln(x) + 412$	$y = \text{cost of BIPV system [€/ m}^2\text{]}$ $x = \text{peak power of the system [kWp]}$
Initial cost per surface	€/ m ²	500	Initial cost per surface when the number of panels on a surface is different from zero
Battery cost			
(assumption : lithium-ion battery)			
Maximum discharge	%	80	Applied so as not to damage the charging capacity of the battery
Number of cycles	cycles	2200	Which allows to determine the lifetime of a battery

Function of battery cost	€	$y = 962.05 * x^{-0.207}$	y = unitary cost of battery [€] x = capacity of battery [kWh]
Battery price reduction rate	%/y	1.5	Applied because battery prices will decrease in the coming years
Initial cost of battery	€	200	Corresponds to the use of a regulator

7 OPTIMIZATION RESULTS

7.1 Optimization results for the first case

The simulation described above is written in Python and it can now be used with the XTREME software [7] to perform multi-objective optimization. Multi-optimization will minimize the total cost of electricity over 25 years and the setup cost. To achieve this, XTREME will modify and search for the best value of the design variables (number of panels per surface area and battery capacity) in order to minimize both the setup cost and the electricity cost over 25 years.

The simulation on XTREME was launched with a MGA (Multi-objective Genetic Algorithm) with the following selected characteristics: 200 reproduction cycles and 200 individuals. This simulation lasts on average 6 hours with a time per reproduction cycle of 109.43 seconds. Figure 7-1 shows the results obtained during the last design cycle. These results, plotted on a graph of the evolution of F2 (Setup cost) as a function of F1 (Electricity cost), allow to obtain a highly detailed Pareto front. This curve is composed of 219 calculation points corresponding to the combinations of variables giving the most optimized results.

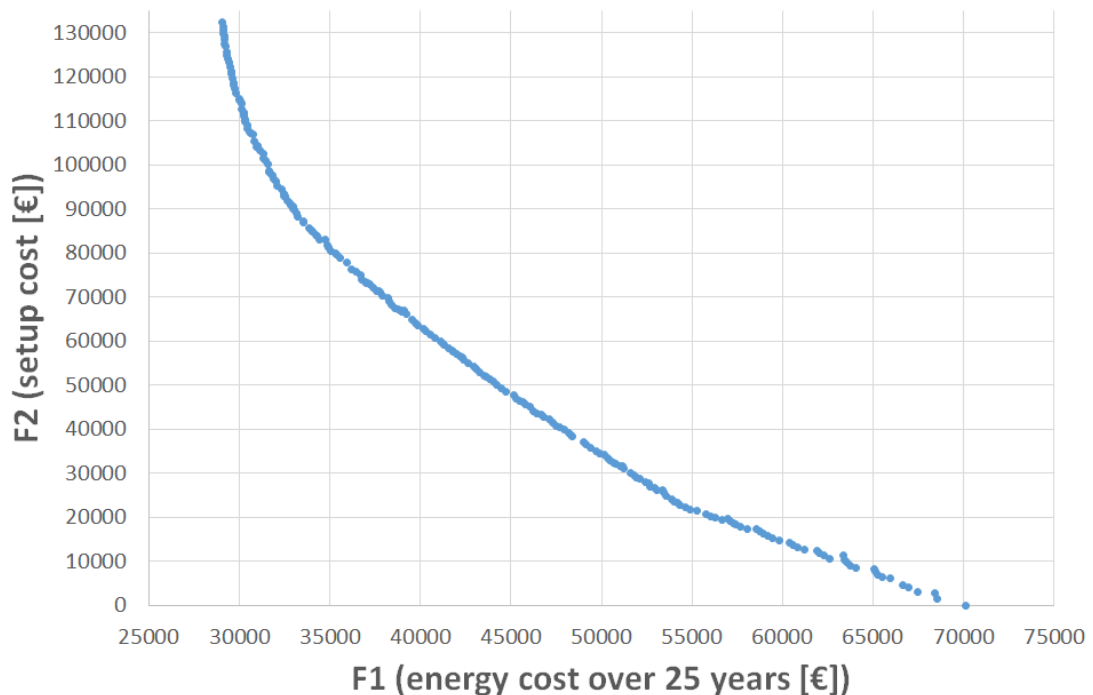


Figure 7-1 : Pareto front of first simulation

It can be interesting to see how variables evolve when the cost of investment is increased. This will show which surfaces are the best and should be filled before others. To do this, the Figure 7-2 shows the evolution of each variable according to the setup cost. The data were previously made non-dimensional to see the variation of each variable from 0 (no module or no battery) to 1 (maximum number of modules on the surface or maximum capacity of the battery). With this graph, we can therefore know from which point of the Pareto front each surface begins to be filled.

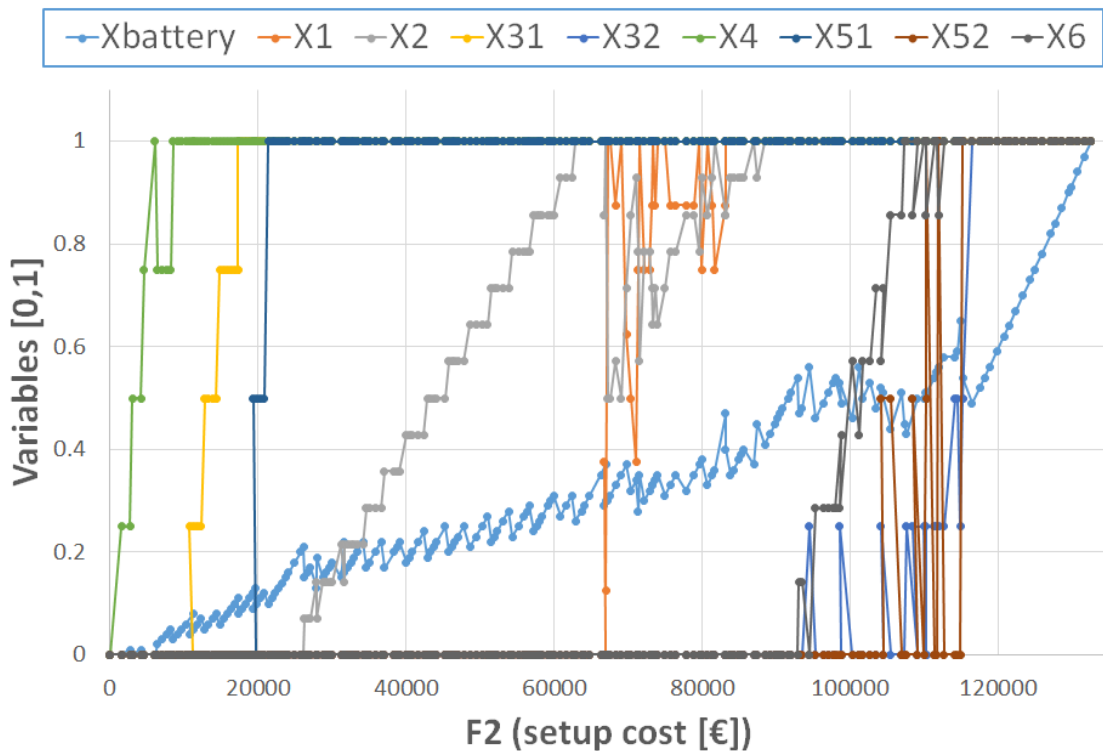


Figure 7-2 : Evolution of variables

Figure 7-3 shows the order in which the surfaces are filled and when the battery capacity begins to increase.

It can be observed that the first surface to be filled with modules is surface 4, which is a roof surface. This looks logical given that roof surfaces are the most exposed to the sun. In addition, even though there are other roof surfaces, surface 4 is preferred because there is no shading at all. After the surface 4, it is the surface 31 followed by the surface 51 that are chosen by the optimizer. This seems also logical given that these are two roof surfaces and are therefore much more exposed to the sun than the facade surfaces. In addition, these sub-surfaces do not have any shading.

After the roof surfaces, it is the surface 2 (East/South) that starts to be filled followed by the surface 1 (South). This again seems very consistent since the installation of BIPV modules requires more financial investment on the façade than their placement on the roof. The large space between the time the surface 2 and the surface 1 are filled can be easily justified. Indeed, surface 2 can accommodate 14 panels. The variable X2 can therefore take 14 different integers, which is much more than other surfaces. This justifies the fact that surface 1 is not filled immediately after surface 2. Finally, it can be noted that surface 6 (West/North) is the last façade surface to be filled. This can be explained by the fact that it is a north-west facing surface and is therefore very badly exposed to the sun. It is therefore not interesting to place solar panels on this façade.

Finally, it can be seen on Pareto front that a simulation point is located on the abscissa axis. This point corresponds to a situation where the cost of the investment in the BIPV installation is zero.

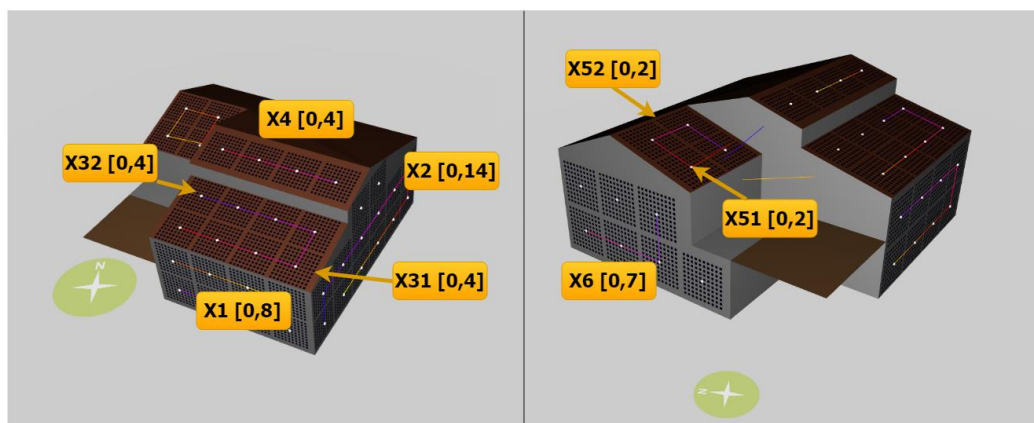
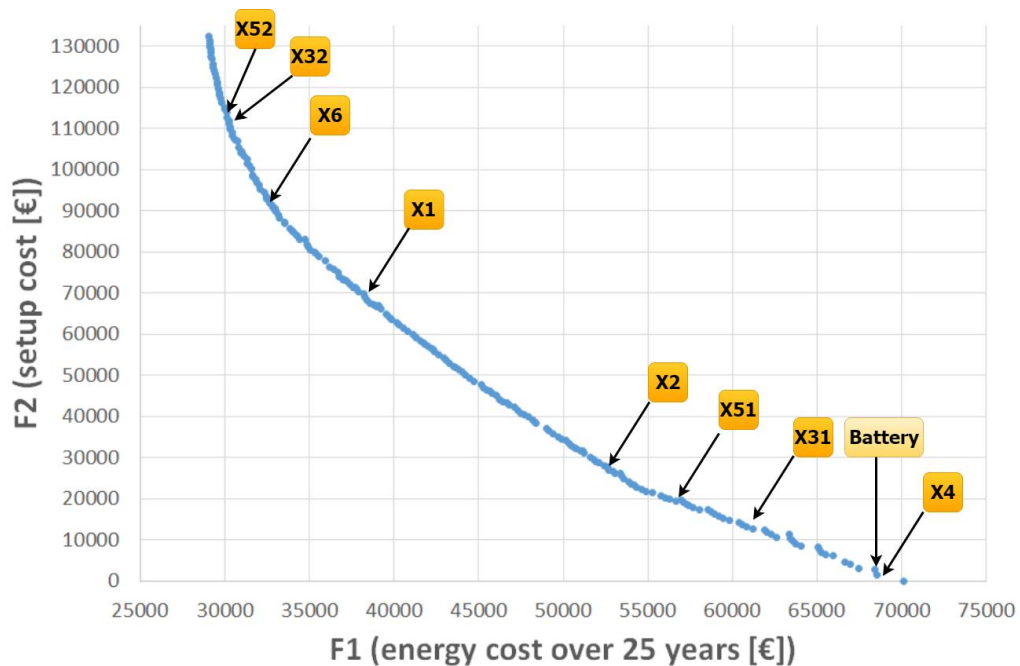


Figure 7-3 : Pareto front and design variables

Figure 7-4 highlights the results obtained for the different **characteristic points**. The first line corresponds to the point located on the abscissa axis, i.e. the point with 0 euro of investment. The second line, highlighted in orange, corresponds to the point giving the most advantageous overall amount over 25 years and therefore corresponds to the installation of one BIPV module on roof surface 4. The following points correspond to the points represented on the Pareto front of the Figure 7-3 (i.e. the points where some variables start to be different from zero). The last line corresponds to the last point of the Pareto front, i.e. the point with the lowest energy cost over 25 years and the highest setup cost. For each characteristic point, it is possible to visualize the value of the peak power of the installation in Wp as well as the value of the two objectives F1 (energy cost over 25 years) and F2 (setup cost).

According to this first study, investing in a BIPV system (BIPV and not BAPV) with a battery is not financially attractive. However, these results are based on a number of data that are known now but will likely change in the future or be different in another European region:

- The cost model is based on the current data and pricing model: slightly higher price of BIPV compared to BAPV in the case of residential roof systems
- No financial incentive for the installation of solar PV modules
- Specific case of the cost and financial incentives in the Walloon region in Belgium have been used.
- A residential house is considered with relatively low consumption during the day.
- There is no adaptation of the consumption profile of the house to be more in line with this type of house equipment (load shift, electric car, ...), while this could positively impact the self-consumption and the economics of the studied case

Therefore, this was the opportunity to use the developed model in order to study the impact of some of the above hypothesis on the optimization results. In particular, what could be the result if the electricity price increases much more than the inflation, what if the BIPV cost is reduced (the goal of this EU project), etc.

Xbattery [kWh]	X4	X31	X51	X2	X1	X6	X32	X52	Total power [Wp]	F1 [€]	F2 [€]	GLOBAL [€]
0	0	0	0	0	0	0	0	0	0	70125.9876	0	70125.9876
0	1	0	0	0	0	0	0	0	300	68520.7135	1562.15606	70082.8695
1	1	0	0	0	0	0	0	0	300	68430.3414	2724.20606	71154.5475
4	4	1	0	0	0	0	0	0	1500	62630.4376	10729.1682	73359.6057
9	4	4	1	0	0	0	0	0	2700	56641.9443	19414.0225	76055.9668
15	4	4	2	1	0	0	0	0	3300	53064.4787	26238.3649	79302.8435
29	4	4	2	12	3	0	0	0	7500	38976.0644	66730.3389	105706.403
47	4	4	2	14	8	1	0	0	9900	32472.7629	93071.3097	125544.073
51	8	14	4	1	4	2	2	6	12300	30295.1807	110181.273	140476.454
54	4	4	2	14	8	7	2	2	12900	29971.7809	115141.505	145113.286
100	4	4	2	14	8	7	4	2	13500	29059.3599	132420.282	161479.642

Figure 7-4 : Numerical results of the characteristic points

8 SENSITIVITY ANALYSIS

In this last chapter, the results of a sensitivity analysis are presented. The goal of this sensitivity analysis was to investigate the effect, on the optimization result, of a number of parameters of the simulation. Three different studies will be carried out. First of all, the influence of decreasing the **BIPV end-user cost**. Then, several simulations with higher **electricity costs** will be performed and discussed. And finally, a study covering both cases (decrease in BIPV end user-cost and increase in the electricity cost) will be presented.

8.1 Decrease in BIPV end user cost

First, the study of decreasing the BIPV end-user cost is carried out. This analysis is interesting since one of the aims of the BIPVBOOST project is to bring down costs of BIPV multifunctional solutions. To do this, a reduction rate (from the initial cost until -60%) has been applied to the total cost of the BIPV and no reduction of the battery price. Figure 8-1 shows the Pareto front for the different simulations. The basic simulation, which was presented in Section 0, corresponds to the initial Pareto front. The other curves correspond to the Pareto edges of the simulations with an applied BIPV cost reduction rate ranging from -10% to -60%.

First of all, as the BIPV price is reduced, the points of the Pareto front are moved downwards which seems logical given that F2 decreases while no modification at F1 level has been made. In terms of results, the lower the cost of the BIPV, the more financially interesting the results are. Indeed, as a reminder, during the initial simulation, the point where the overall sum (F1 + F2) was the lowest was the installation of a single panel on surface 4, which is the best oriented roof surface and most exposed to the sun throughout the day. Then, the second most interesting point was the one with 0€ of investment, i.e. no installation. When BIPV prices are lowered, it becomes clear that more and more points corresponding to a larger number of panels have become more attractive than the point at 0€ of investment.

Figure 8-2 shows these points and the amounts of the different costs (F1 = energy cost over 25 years, F2 = setup cost, Global = F1+F2). The first line shows the point with a zero setup cost, which is a point that belongs to the Pareto front of each simulation. For each simulation, the points being better than the point at 0€ of investment are included. For the -50% and -60% simulation, there are 25 and 39 points respectively, but they are not all represented in this figure. It is therefore clear that this number of interesting points increases as the BIPV end-user cost are reduced.

If we compare these points on the different Pareto fronts, we actually realize that the points become financially interesting when they are located under the line represented in black on the Figure 8-1. This line actually corresponds to the constant overall price over 25 years (Global "constant"). When the points are located below this line are results where investment in a BIPV system becomes cost-effective.

Finally, on the same graph we see that despite the decrease in the price of BIPV modules, the curves do not move beyond a certain limit along the F1 axis (electricity cost) corresponding to an approximate value of 30.000€ to be paid over the 25 years for electricity. This is due to the fact that even if the maximum of BIPV modules are placed on the building (45 modules maximum), the production over 1 year will not be sufficient to compensate for the average consumption of 10.000 kWh/year that has been applied through the load profile. Therefore, with such a system and such an average annual consumption, it is not possible to be in complete self-consumption for this residential building. In addition, adding a battery with a large capacity does not change these findings. Indeed, even if the battery has a capacity of 100 kWh, it is not possible that the electricity produced by the panels are sufficient to feed enough energy in the house. The simulation results are therefore very dependent on the chosen load profile and thus, in this case, on the chosen average annual consumption. If this is reduced, it is likely that the Pareto front would be moved to the left.

This study therefore shows that it would be necessary to reduce the cost of BIPV modules by between 40 and 50% in order to have a wide choice of cost-effective solutions of BIPV coupled with battery storage. The advantage of having a wide choice of solutions is that, depending on the needs and the amount you are able to invest, you can choose a solution that suits you from among the most profitable solutions provided after optimization.

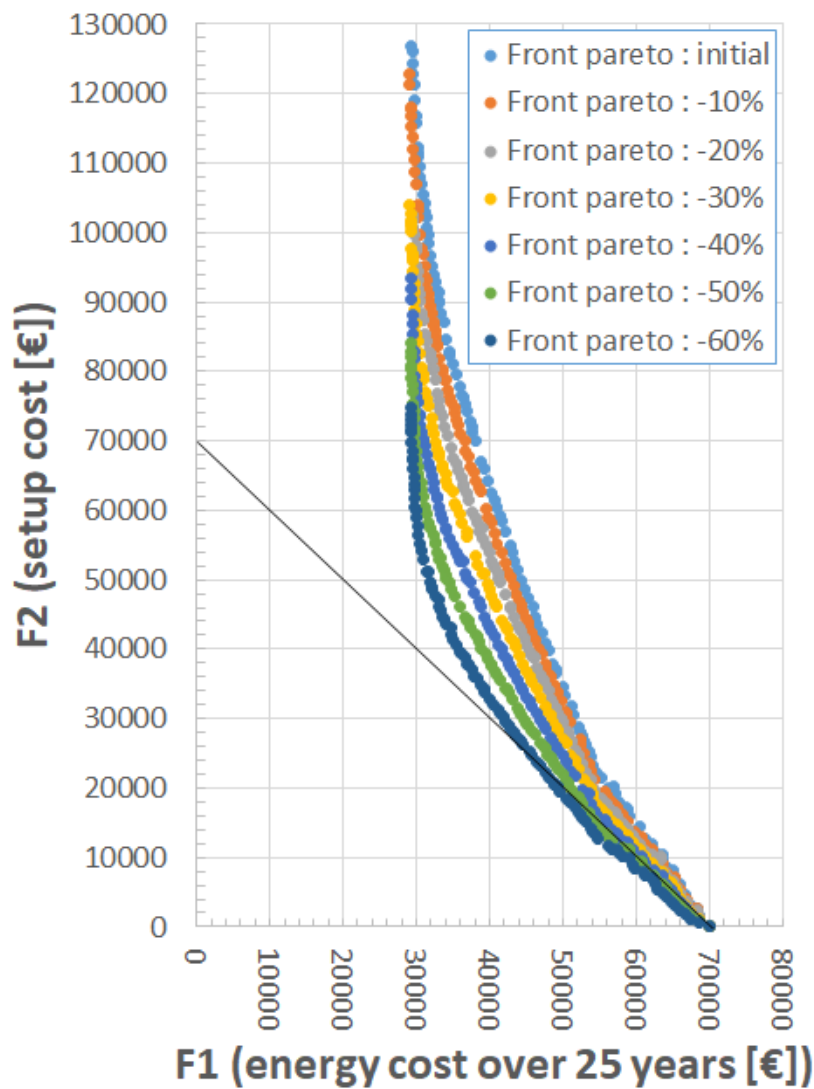


Figure 8-1 : Comparison of Pareto fronts - BIPV price reduction

	Battery [kWh]	X1	X2	X31	X32	X4	X51	X52	X6	F1 [€]	F2 [€]	GLOBAL [€]
Setup cost = 0€	0	0	0	0	0	0	0	0	0	70125.98764	0	70125.98764
Initial simulation	0	0	0	0	0	1	0	0	0	68520.71347	1562.1561	70082.86952
Simulation : -10%	0	0	0	0	0	1	0	0	0	68520.71347	1405.9404	69926.65391
Simulation : -20%	0	0	0	0	0	1	0	0	0	68520.71347	1249.7248	69770.43831
	0	0	0	0	0	2	0	0	0	67441.99018	2465.482	69907.47219
Simulation : -30%	0	0	0	0	0	2	0	0	0	67441.99018	2157.2968	69599.28694
	0	0	0	0	0	1	0	0	0	68520.71347	1093.5092	69614.2227
	0	0	0	3	0	0	0	0	0	66644.16117	3209.866	69854.02718
Simulation : -40%	0	0	0	0	0	2	0	0	0	67441.99018	1849.1115	69291.10169
	0	0	0	0	0	3	0	0	0	66630.26198	2751.3137	69381.5757
	0	0	0	0	0	1	0	0	0	68520.71347	937.29363	69458.0071
	0	0	0	0	0	4	0	0	0	65929.35758	3647.2715	69576.62908
	0	0	0	4	0	1	0	0	0	65304.89891	4584.5651	69889.46404
Simulation : -50%	0	0	0	0	0	3	0	0	0	66630.26198	2292.7614	68923.02341
	0	0	0	0	0	4	0	0	0	65929.35758	3039.3929	68968.75049
	0	0	0	0	0	2	0	0	0	67441.99018	1540.9263	68982.91644
	10	0	0	4	0	4	2	0	0	55274.65896	13792.783	69067.44159
	0	0	0	4	0	1	0	0	0	65304.89891	3820.4709	69125.36985
...
Simulation : -60%	11	0	0	4	0	4	2	0	0	54878.25271	12737.789	67616.042
	9	0	0	4	0	4	1	0	0	56641.94429	11182.186	67824.13012
	12	0	0	4	0	4	2	0	0	54645.91191	13197.983	67843.89481
	11	0	1	4	0	4	2	0	0	54119.53519	13762.042	67881.57766
	10	0	0	4	0	4	1	0	0	56270.68605	11660.962	67931.64768

Figure 8-2 : Best results for each simulation – BIPV price reduction

8.2 Increasing electricity costs

The next analysis will allow us to observe the influence of an increased electricity costs. An increase rate was applied to the total cost of electricity over 25 years. The rate of increase is therefore applied to the price in off-peak and peak hours, the annual fixed charge and the resale price of electricity.

Figure 8-3 allows to compare the Pareto fronts of the different simulations. As in the previous case, the initial Pareto front corresponds to the base case without the application of a special rate. Then the simulation curves with increase rates from 20% to 100% are represented.

It is directly concluded that the higher the electricity costs are, the more the Pareto front moves to the right, which seems consistent. However, another much more interesting observation can be made about the appearance of the curve. Indeed, the Pareto front of the initial simulation looks very vertical. Therefore, when electricity costs increase, the appearance of the curve becomes much less vertical and rounds out. It is therefore interesting to place on the graph the lines representing a constant global cost whose origin is placed at the point at 0€ of investment for each simulation. As a consequence, it is observed that the higher the electricity price, the more points on the Pareto front are located under the corresponding line. As explained in the previous case, these points correspond to more interesting results than the zero investment. So that's where it gets interesting. Indeed, if the cost of electricity was more expensive, it would be much more advantageous and beneficial to invest in the installation of a BIPV system.

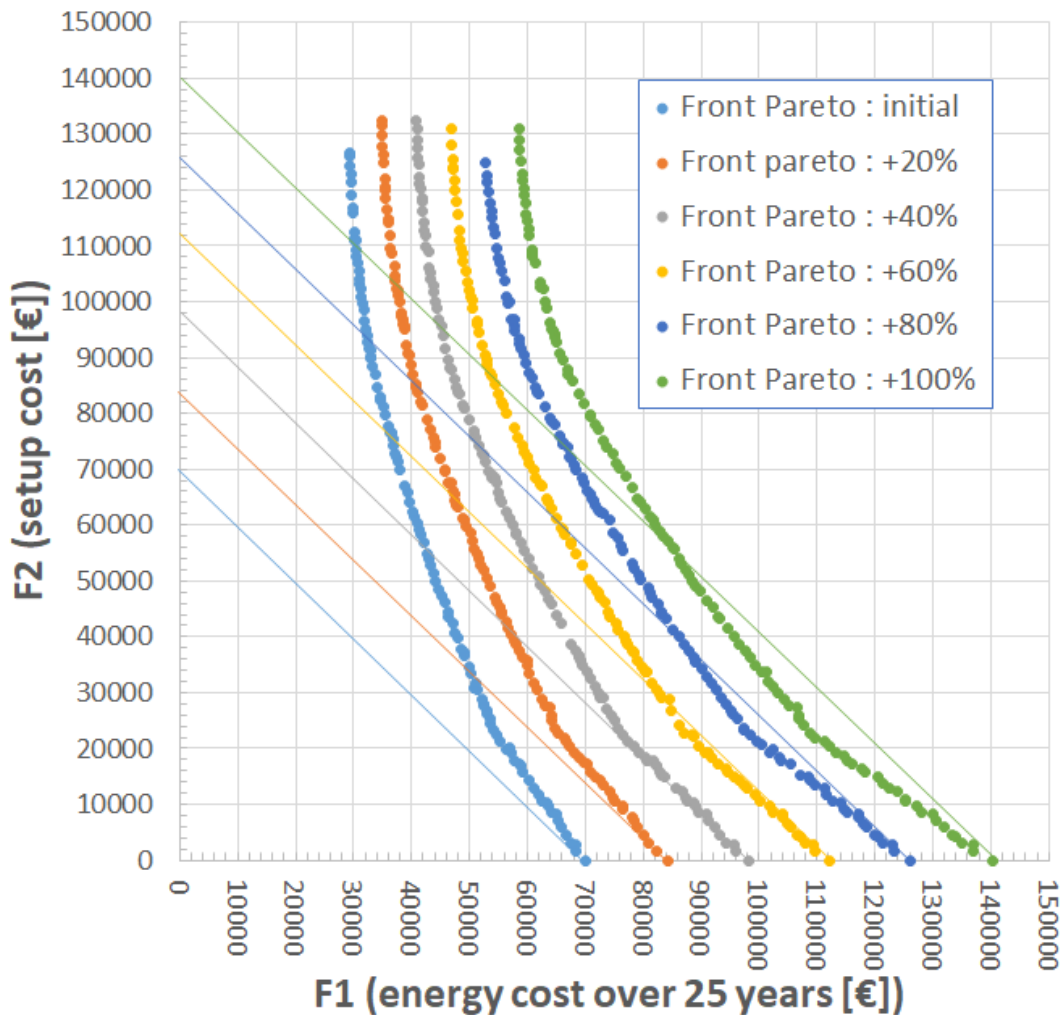


Figure 8-3 : Comparison Pareto fronts - Increasing energy costs

8.3 Decreasing BIPV end user cost and increasing electricity costs

Finally, another study that may be interesting is to combine the two cases seen above. It is therefore necessary to apply simultaneously:

- The decrease in the cost of BIPV modules and,
- The increase in the cost of energy.

Figure 8-4 compares the Pareto fronts obtained for the different simulations. As before, the initial Pareto front corresponds to the basic simulation without the application of a reduction or increase rate. Then several simulations were carried out. The first is where BIPV's price has been reduced by 10% and the price of energy increased by 10%. The rates were each time increased in steps of 10%.

First of all, it can be noted that due to the increase in electricity prices, the curves are moving to the right, i.e. the F1 goal increases, which was observed in the 2nd study carried out. Then it can be also observed that the values of F2 decrease, as it was obtained during the 1st study. However, the combination of the two makes the curves become much more quickly rounded down. In addition, it can be seen that points are located much more quickly on and below the line of a constant overall amount. As a reminder, these points

correspond to the most interesting results since they have a lower total cost (F1+F2) than if there were no installation.

These results show that starting from a rate modification between 20 and 30% on both costs, the results become very interesting and would allow to obtain a wide range of cost-effective solutions with BIPV. This is exactly the goal of the BIVBOOST project, to reduce the cost of BIPV systems. The increase in energy price of the same 30 % is something possible also in the next future but out of scope of this project.

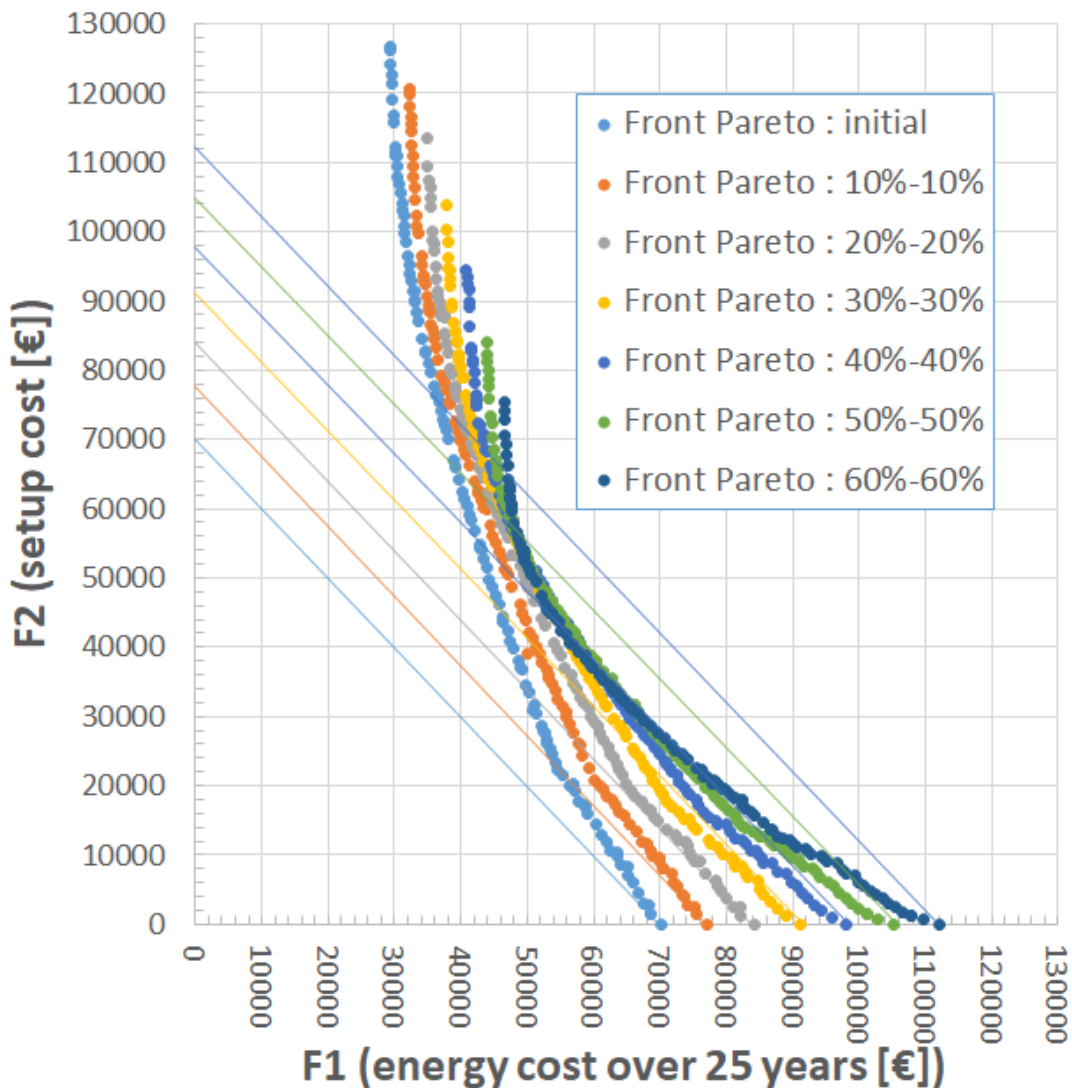


Figure 8-4 : Comparison of Pareto fronts - Decreasing BIPV cost + increasing costs of energy

9 CONCLUSION AND FUTURE IMPROVEMENTS

This report shows that a first approach and a first prototype was developed capable to find the set of optimal solutions for the setup of BIPV solutions. The goal of this task and deliverable are therefore met.

In addition to that, the prototype has been used in order to gain experience with it and to perform a number of very interesting studies based on different costs parameters and scenario. The results obtained after the optimization with XTREME [7] are explained in the report, seems consistent and already allowed the consortium to understand important factors. This optimization prototype is already very complete and allows the user to adapt its parameters to its configuration and run various optimizations in an efficient way.

The prototype can be improved mainly on several points linked to the simulation part:

- A key input is the load profile of the building which is outside the scope of the present deliverable. However, a better prediction of the load profile would be important before starting the optimization of any building.
- Another point that needs to be improved is the battery model. The current prototype counts the number of charge and discharge cycles of the battery in order to determine its lifetime. The algorithm counts a cycle when the battery reaches its maximum and then its minimum charge. However, since electricity consumption is much higher than electricity production due to the high load profile, the battery is very rarely recharged to its maximum and therefore the number of cycles does not increase. As a result, the simulation model almost never takes a replacement battery into account. This is why it will be necessary to improve this part in the simulation process in order to have a number of cycles of about 360 per year, which is an average value closer to reality.
- This prototype could also be improved to choose the type of panels among a list of possibilities.
- It would be interesting to complete the script with some more post-processing capabilities in order to be able to better analyse and understand the results provided by the optimizer. Indeed, for the time being, the script provides, for each optimized point, the energy cost over 25 years and the installation cost in €. In the future, it would be interesting to know the hourly or monthly profile of electrical consumption, electrical production, electrical auto-consumption, electricity sent to the grid, battery charge, ...
- Some hypotheses could be checked after this first prototype version:
 - For example, the lifetime of the micro inverter is assumed to be 25 years in this document and must be checked carefully, since the replacement of micro inverters is not taken into account in this first simulation model.
 - The yearly decrease of battery price is actually a nominal rate, i.e. already taking into account the effect of inflation.
 - Next to the load profile, the total electricity amount assumed in this work must be checked in details such as the energy amount for hot water and heating.

As a first complete and efficient prototype is now available, other test cases could be carried out on different buildings (office, company, school, etc.) and in priority on the BIPVBOOST demo sites. Carrying out the simulation and optimization on other test cases will allow us to better understand this first prototype if the results provided seem consistent and close to reality.

The aims of the BIPVBOOST project being to reduce the costs of BIPV solutions, the prototype develop in this task offer a very powerful tool to study and obtain various solutions for minimizing the BIPV cost.

This optimization prototype shows the way to go further in the development of the integrated optimization module inside the BIMsolar® [\[1\]](#) software. The optimization process currently takes between 1 and 2 hours to provide the Pareto front. This optimization module will therefore be a module that is not run instantaneously on one side but on the other side it provides a complete set of solutions along the Pareto front.

The whole set of solutions does not impose anything to the architects, it simply provides a design tool to propose them several different solutions. The architects are therefore free to choose one solution or the other and the results of the tool will tell them the economic performance of the chosen solution.

Finally, in the next phase, it could be considered using the “competitiveness” metric introduced in D1.1 [\[3\]](#), which takes into account all important factors (total end-user cost, CAPEX, OPEX, generated electricity and its valuation when self-consumed or not). This metric might facilitate the interpretation of results for non-experts.

10 REFERENCES

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