"CLIENT II - International Partnerships for Sustainable Innovation"
LoSENS: LOCAL SUSTAINABLE ENERGY NETWORKS IN SENEGAL

LoSENS

WP4b:

Photovoltaic System & Energy Storage

WP4: Project Technicalities & Method

IfaS Institut für angewandtes Stoffstrommanagement

COMMUNE DE SAINT-LOUIS

SPONSORED BY THE Federal Ministry of Education and Research

Birkenfeld, March 28, 2024

SUBJECT: ***WP4b: Photovoltaic System and Energy Storage***

LOCATION: City of Saint-Louis, Senegal

CATEGORY: Knowledge Transfer and Feasibility Assessment

SYNOPSIS: This report presents the findings of ***city Saint-Louis*** model region as part of ***"Local Sustainable Energy networks in Senegal"*** project with the objective of developing ***a Photovoltaic System and Energy Storage***. This report documents the various stages involved in building a new solar and energy storage system at the UGB. An inventory of existing photovoltaic systems at the university will also be drawn up. In addition to demonstrating the positive (economic, ecological, and social) benefits of a new installation of this kind for middle-class consumers, as exemplified by the Université Gaston Berger, the obstacles to the expansion of solar energy in general will be presented. The methodology deployed at large is Material Flow Assessment where different site measurements and investigations contribute to the establishment of a base data representative of the status quo for solar power potential.

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1 Executive Summary

The electricity shortages facing the university make the photovoltaic and storage system to be installed at the UGB a key factor, which will provide power to certain pre-selected classrooms and offices in the event of load shedding. This will ensure that strategic equipment is always operational, thereby limiting the damage caused by a lack of electricity.

The system was implemented with the ongoing support of our partners, namely KLE, Bonergie and COPERES.

The project involved the following stages:

- Visit to the construction site
- Data collection
- Drafting of specifications and call for tenders
- Economic, ecological and social analysis of the project
- Documentation

The solar system will be producing around 168 MWh of electricity a year as well as avoiding 146 t CO_{2e} of emissions. Moreover, the return on investment for the project is 10.5 years, with an energy production cost of around 0.146 €/kWh (96 XOF/kWh).

2 Methodology

2.1 Existing situation of the PV in Gaston

The University Gaston Berger of Saint-Louis, or UGB for short, is located on the outskirts of Saint-Louis in Senegal. It is a university open to national and international students, who can choose their course of study among the UGB's Training and Research Units (UFR), including Arts and Humanities, Economics and Management, Applied Science and Technology (SAT)[1], etc. The latter offers students the chance to be trained in the field of renewable energies (UGB, 2022). A key specialization that should enable the UGB to do without the load shedding it experiences from Senegal's national electricity company (SENELEC). Indeed, the interruptions caused by power cuts have prompted the UGB to embark on the transition to renewable energies; this ambition is being pursued by the Infrastructure, Innovation and Community Services Commission (Commission 2ISC), which was set up by Professor Abdoulaye DEME after his election as director of SAT[2].

To achieve this objective, which is energy autonomy, small decentralized photovoltaic systems are being successively installed on the roofs of the various buildings of the Université Gaston Berger. These are listed in Table 1. It is important to note that all these solar systems are in good working conditions.

Table 1 | Existing Photovoltaic Systems at L'UGB[3]

LOCATION	POWER [kWp]	STORAGE SYSTEM	DATE OF COMMISSIONING	OBJECTIVES
Computing Center	07	4 batteries of 12 V and 100 Ah each		Self-sufficiency of the computer server room
CEA MITIC[4]	07			Self-sufficiency of the computer server room
UFR SAT	06			Self-sufficiency of Physics and Computer Science laboratories
Building I (UFR SAT)	3.15		April 20, 2022	Training for students enrolled in the Renewable Energies Master's program and, above all, guaranteeing continuity of service in practical laboratories.

[1]In partnership with 3 other public higher education institutions. This Master's program, which was supported by PESEREE :https://www.daad.de/de/infos-services-fuer-hochschulen/weiterfuehrende-infos-zu-daad-foerderprogrammen/peseree/

[2] Data collected on 28.02.2023 from the chairman of the 2ISC commission, Mr. Amsata NDIAYE

[3] Center d'Excellence Africain en Mathématiques, Informatique et TIC (CEA MITIC): ICT (Information and Communication Technologies)

As indicated by the data collected from the Chairman of the 2ISC Commission, Mr. Amsata NDIAYE, effective measures are not only being taken to enable the UGB to become energy self-sufficient, but emphasis is also being placed on practical training for students. A total of 23.15 kWp (kilowatt peak) has been installed at Gaston Berger University. This enables the coverage of the desired load requirements. As a result, SENELEC only intervenes when this output is insufficient to supply loads. The 3.15 kWp solar system, whose components were acquired thanks to the STAIRE[5] project, covers the electrical demand of the "IL01" physics laboratory in building "I". An extension of this project is planned to supply the teachers' offices in the vicinity of this laboratory[2].

While the STAIRE project is the fruit of a partnership between the Faculty of Applied Sciences at the University of Neu-Ulm in Germany and the Université Gaston Berger, through the UFR SAT, it is far from being the last partnership fruit to be enjoyed by the Université Gaston Berger, as part of the LoSENS project, a larger photovoltaic system will be installed on the roof of the UGB's "A" building.

This new LoSENS project (Local Sustainable Energy networks in Senegal) is funded by the German Federal Ministry of Education and Research (BMBF), through its CLIENT II initiative (International Partnerships for Sustainable Innovations). The CLIENT II support measure encourages international partnerships in the fields of climate, environment and energy. For the first time, it brings together economically oriented international research activities within the "Research for Sustainable Development" (FONA) framework program.

CLIENT II focuses on promoting demand-driven research and development cooperation with partners in selected emerging and developing countries. The aim is to develop and implement innovative, sustainable solutions to concrete challenges in the partner country. CLIENT II is also intended to help strengthen education, research and innovation in Germany, and to support the competitiveness of German companies through cooperation with the partner countries concerned (PtJ, n.d.).

Figure 1 below explains why building "A" was chosen for this project: on the one hand, it is close to a 400 kVA transformer substation; on the other hand, it is close to the other rooms intended to accommodate the students; both aspects will facilitate possible connections.

[5] Data collected on 28.02.2023 from the chairman of the 2ISC commission, Mr. Amsata NDIAYE

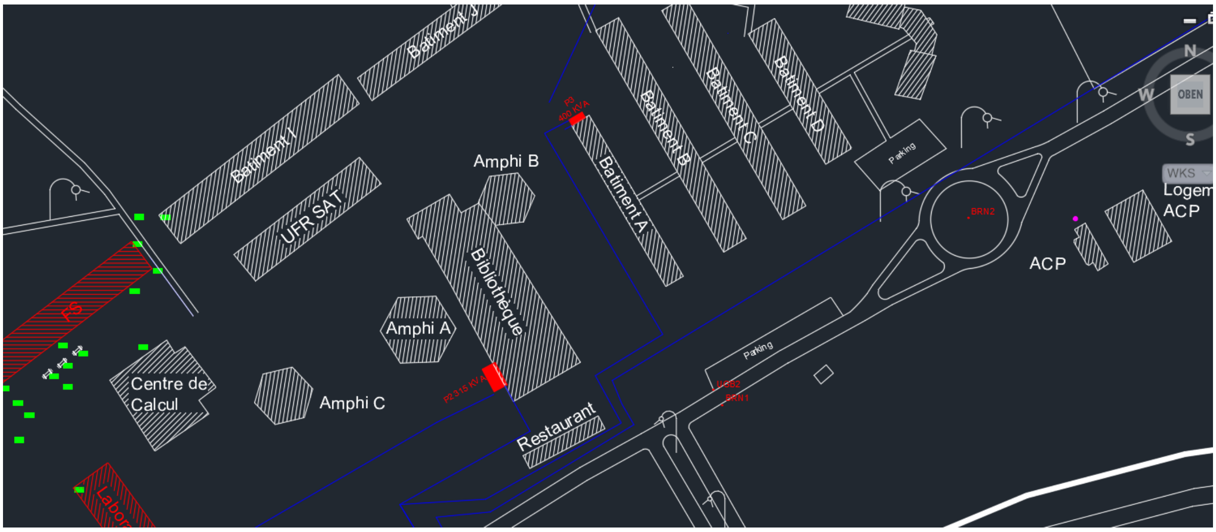

Figure 1 | Partial Plan of the UGB. This Image is taken from a Reconstruction made with AutoCAD Software, (© IfaS)

2.2 Solar PV System Description, Components and Operation

Le The LoSENS project is a pilot project. The installation of a photovoltaic (PV) system as part of this project remains a test, which will enable us to confront the realities in the field, understand how such a system works and so on. The information gathered during the monitoring phase will provide a solid database for the sizing of a larger system, which will bring Gaston Berger University closer to energy autonomy, as well as other universities and towns in Senegal in general.
The 100 kWp PV system will cover part of the energy demand of building "A". The system will be dimensioned in such a way that, in the event of load shedding, some of the solar modules installed will continue to supply energy to the pre-selected premises of said building; to do this, the modules will be connected to a battery inverter. In addition to this component, the following elements will be connected to the PV system:

- Inverters: to convert direct current from solar modules into alternating current;
- A Battery-based storage system of up to 100 kWh: to store excess energy produced;
- A resale meter and a bi-directional meter: to analyze the flow of energy;
- A junction box: for connecting a circuit, as well as distributing the electrical circuit to various devices (sockets, lighting, etc.).

In the next section, we'll run a simulation to estimate the system's energy output.

2.3 Photovoltaic System Sizing using PV*SOL Software

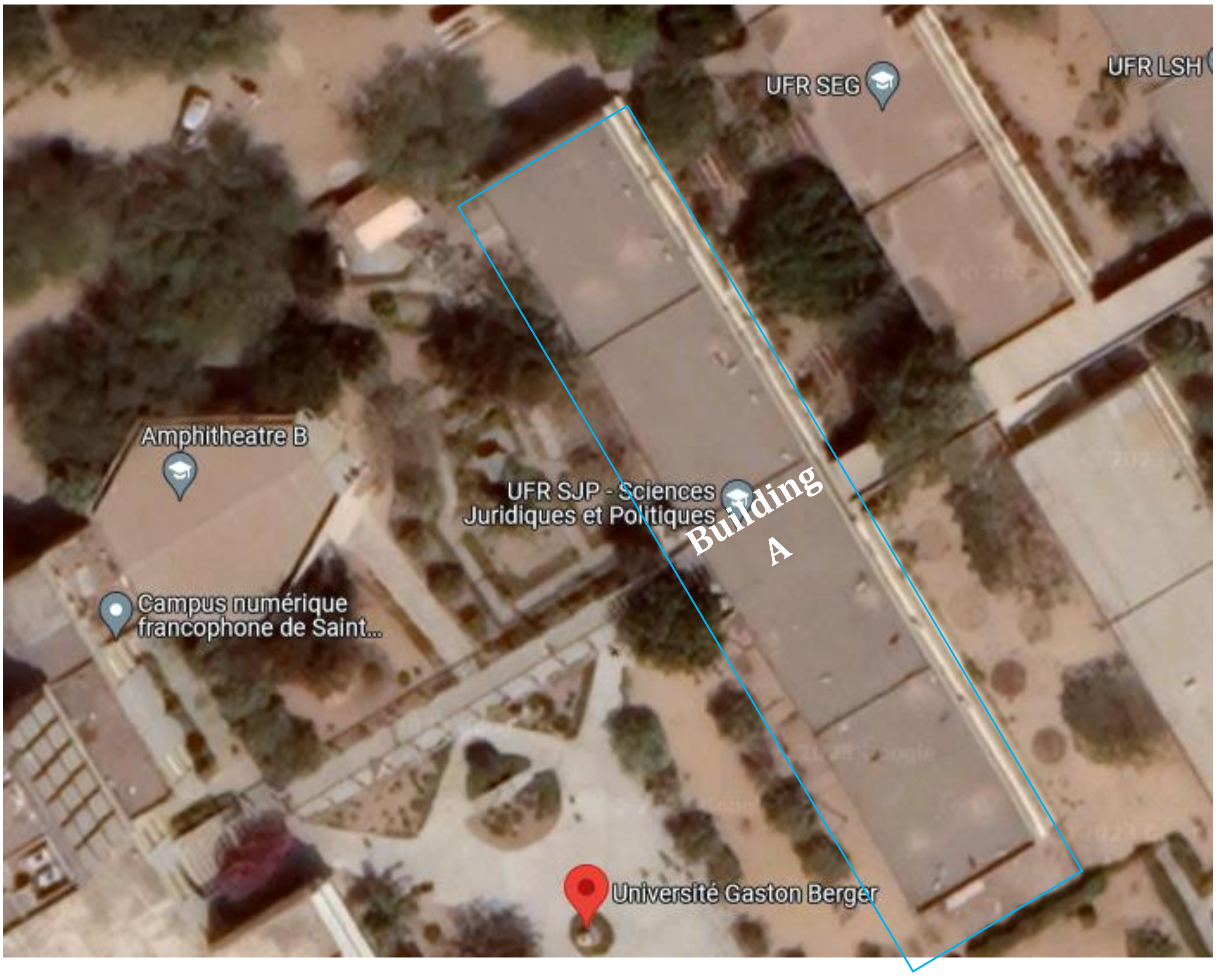

Figure 2 | Building "A" at Université Gaston Berger (Circled in Blue), (Google Maps, n.d.) [6]

PV*SOL is a powerful tool for simulating photovoltaic systems. It can be used to simulate photovoltaic systems connected to a consumer and the grid, and to island or non-island storage systems. PV*SOL's diversified database gives the user a free choice of integrating the desired components (modules, inverters... from a desired producer) into the simulation. The advantage of such a database is that it is instantly updated. However, results cannot be obtained without prior information. Before selecting the components, the surface area available for installation, the location of the system, the orientation of the building on which the system will be built, etc. are all necessary data.

According to google maps, building "A" is 74.7 m long and 12.24 m wide, giving a surface area of around 914 m^2 available for the PV system. As far as the orientation of the modules is concerned, the south-facing direction is advantageous, since a module oriented in this direction receives solar radiation all day long. The orientation of the building does not favor this arrangement, which is why the modules were oriented to the south-west and north-east, i.e. at 238° and 58° respectively.

[6]Site in Google Maps: https://www.google.com/maps/place/Universit%C3%A9+Gaston+Berger/@16.0617969,-16.4227365,203m/data=!3m1!1e3!4m6!3m5!1s0xe9550ba9ce4f41f:0x21b4c5b97ac744d2!8m2!3d16.0615636!4d-16.4224667!16s%2Fm%2F02rrxcb

Compared with Western countries, the angle of elevation of the sun γ gamma is sufficiently large at the equator, as it is in Senegal, where the project will be carried out. As a result, the modules don't need to be high enough. Roof construction does, however, require the use of frames, as can be seen on the right of Figure 3. The various parameters used for the simulation are shown in Table 2, and remain just one of many possibilities.

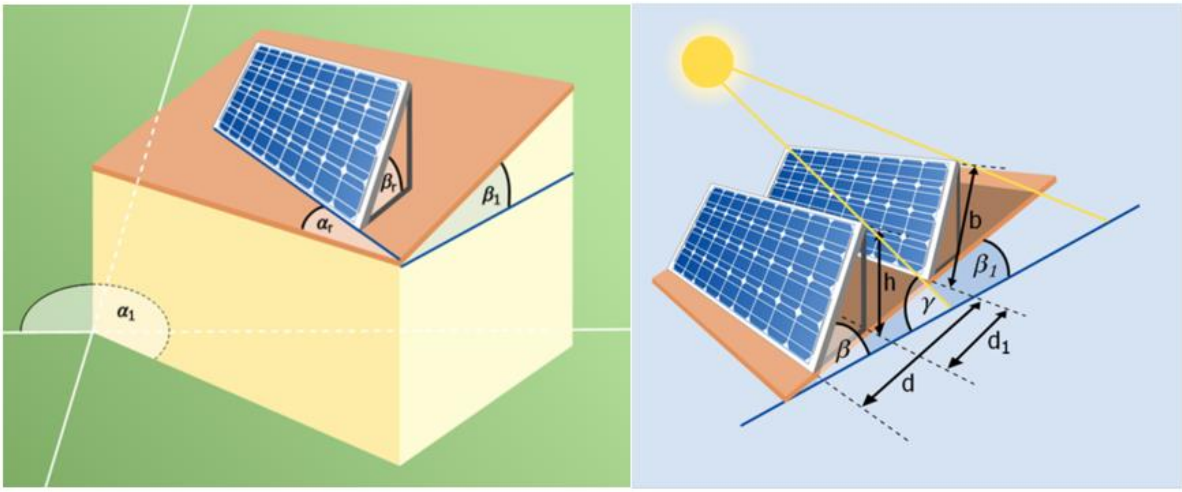

Figure 3 | Module Orientation and Mounting System, (© IfaS)

Table 2 | System Design Parameters

ORIENTATION	*VALUE*	*UNIT*
Module inclination β	10	°
Row distance d1	0.314	m

Installing a solar module on a roof means increasing the load the roof is designed to support, which is why a roof statics calculation is required prior to installation.

2.4 Photovoltaic System Installation

This part of the project will involve building the PV system at L'UGB. While it is certain that a capacity of around 100 kWp will be installed with a storage system, details of the specific characteristics of the components are missing, as these will depend on the bids submitted to IfaS. For this reason, the Result section will list the system components used for the forecasts, together with the expected results, and the system components installed with accessories, together with the actual results.

The following steps preceded the installation phase:

- Prior to installation, it was necessary to obtain authorization to build the photovoltaic system, lest the system be destroyed, in accordance with Senegal's renewable energy law. A request was sent to the Senegalese Minister of Petroleum and Energy, who signed the authorization for the construction of the photovoltaic system at Gaston Berger University on December 29, 2022;

- A technical check of the bids received was also carried out.

Verification of the wiring plan: This involves checking that the proposed wiring has been correctly installed. The criteria checked are shown in Table 3 (Haselhuhn & Hartmann, 2010).

Table 3 | Recommendations for Designing a Photovoltaic System

CONDITIONS (TEXT)	***CONDITIONS (ABBREVIATION)***
Total power of connected modules less than or equal to Maximum AC power of inverters	$n^7.s^8.P_{MPP}$ <= $P_{WR,Max}$
Maximum DC current of connected modules less than or equal to maximum inverter current	$s.I_{SC}$ <= $I_{WR,Max}$
Maximum DC voltage of modules connected at -10° less than or equal to Maximum AC voltage of inverter	$n.U_{OC}$(-10°C) <=$U_{IN,Max}$
The rated voltage of modules connected at 25° is within the inverter's rated power range.	$U_{WR,Min,MPP}$ <= $n.U_{MPP}$ <= $U_{WR,Max,MPP}$
The rated voltage of modules connected at 70° is within the inverter's rated power range.	$U_{WR,Min,MPP}$ <= $n.U_{MPP}$(70°C) <= $U_{WR,Max,MPP}$
The rated voltage of modules connected at -10° is within the inverter's rated power range.	$U_{WR,Min,MPP}$ <= $n.U_{MPP}$(-10°C) <= $U_{WR,Max,MPP}$

To calculate no-load voltage and maximum voltage at different temperatures, the following equation was used.

$$U(T) = U(STC).\left(1 + \beta.(T - T_{STC})\right) \quad (1)$$

where U is the voltage, T the temperature, B the temperature coefficient and T_{STC} the temperature in the standard test condition.

2.5 Photovoltaic System Monitoring and Comparison of Results with other Sources

Monitoring refers to the permanent surveillance of processes and operations. Extensive monitoring enables errors to be detected at an early stage and reported immediately, so that the owner of the system concerned can take appropriate measures to minimize or avoid losses (Haselhuhn & Hartmann, 2010). In addition to manual monitoring, which involves taking readings and usually visually monitoring the plant, there is also automatic monitoring, which can provide

[7] Number of modules per row
[8] Number of strings

not only values such as meter readings, but also precise information on system components. Figure 4 shows the basic components used to monitor a PV system.

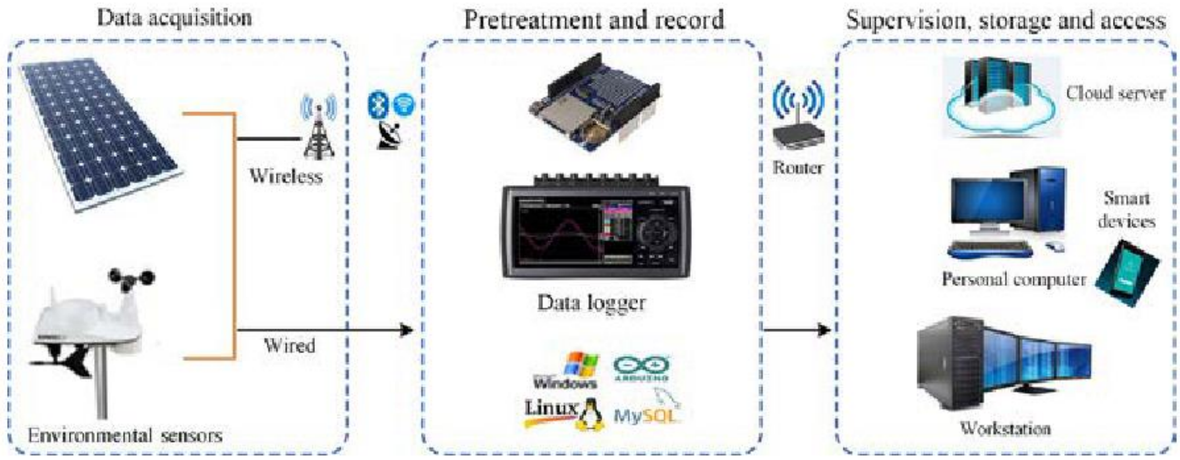

Figure 4 | General Diagram of a PV Monitoring System, (Gorjian & Shukla, 2020)

Sensors (left) measure actual data on site and send them to the signal processing unit (center). After processing and amplification, the results are sent to a PC via a special protocol (right), so that a command can be made based on the data analysis**Fehler! Textmarke nicht definiert.**.

With regard to the various parameters that can be measured, IEC 61724 indicates which parameters are relevant for proper monitoring. These are listed in Table 4.

Table 4 | Parameters Required to Monitor a PV Installation According to IEC 61724

PARAMETER	***SPECIFIC PARAMETER***
Meteorology	Radiation
	Outdoor temperature
PV sections	Module surface temperature
	Output power
	Output Current
	Output Voltage
	Generated Energy
Storage system	Output Current
	Input Current
	Operating voltage
	Power output
	Input power
Load	Power demand
	Current
	Voltage
Electrical network	Network consumption
	Energy injected into the grid

NOTE: To compare results with other sources, the yield of a PV system of the same capacity will be calculated using Solargis energy coefficients. To perform these calculations, the parameters of the selected modules are required. These are listed in the table below.

Table 5 | Solargis and Module Manufacturer Data for Yield Calculation

PARAMETER	***VALUE***	***UNIT***
Specific yield[9]	1,753	kWh/(kWp.a)
Specific yield[9]	2,120	kWh/(m^2.a)
Module parameters, (TallmaxM, 2019)		
Width	1.04	m
Length	2.102	m
Surface	2.19	m^2
Number of modules	224	
Total module area	489.68	m
Total module area without frame	486.1710	m^2
Maximum module efficiency	20.06	%
Module power	450	Wp
Installed capacity	100.8	kWp

[9] © 2020 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis.
[10] 0.5cm has been deducted from the initial dimensions

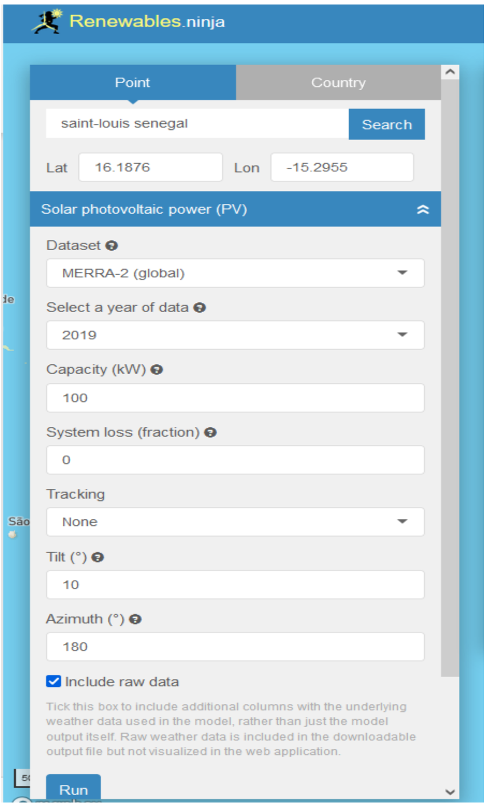

Figure 5 | Simulation Parameter with Renewables Ninja, (© IfaS)

A simulation is also carried out with "Renewables ninja" and the results obtained are compared with those of PV*SOL. The simulation parameters are summarized in Figure 5.

The power and inclination of the system's modules are entered in the parameters. Only the orientation cannot be entered, as in PV*SOL. In this case, south orientation (azimuth 180°) is selected. Losses are neglected during simulation.

3 Results

Figure 6 shows an overview of the photovoltaic generator. All modules have a 10° inclination. As the laws on renewable energies are not detailed enough in Senegal, it was difficult to know the maximum power of the modules dedicated to a rooftop installation. For this simulation, monocrystalline modules of 325 Wp each were chosen because of their efficiency. 312 of these modules were planned for installation on building "A". This equates to an installed power of 104.52 kWp (see Table 6), i.e. a PV array covering 526 m². 10 batteries, each with a capacity of 15.4 kWh, will be connected to this system, along with 5 inverters, whose characteristics will be provided subsequently.

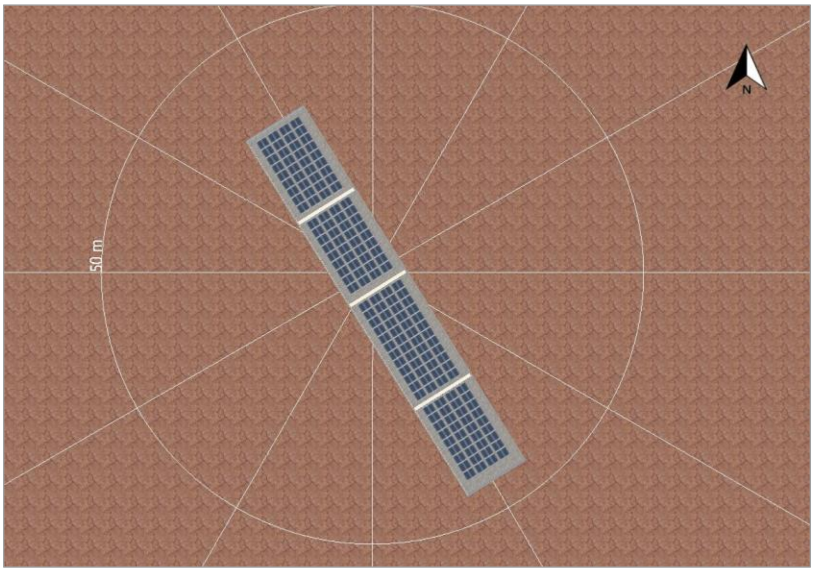

Figure 6 | UGB Photovoltaic System, (© IfaS)

Table 6 | Grid-Connected PV With Electrical Consumers and Battery Systems

CLIMATE DATA	*SAINT-LOUIS, SEN (1991 - 2010)*	*UNIT*
Climate data source	Meteonorm 7.2c3	
PV generator power	104.52	kWp
PV generator area	526.0	m²
Number of PV modules	312	
Number of inverters	5	
Number of battery systems	10	

3.1 Solar PV System Component Parameters

The names of the components used in the simulation will not be indicated at this stage, to avoid any distortion of competition, since a call for tenders will be published for companies wishing to build the system to apply. The purpose of the simulation was to get an idea of the performance of such a system, to draw up a realistic call for tenders, and to have a reference for better analyzing the bids from suppliers, who will be required to submit a wiring plan for the PV system.

The desired parameters for the solar system components are listed in Table 7 to Table 9.

Table 7 | Module and Inverter Parameters

DESIGNATION	DESCRIPTION
Modules >=335 Wp	STC Power : Min. 395 Wp, Module efficiency : Min. 19.9%, Power tolerance (STC): -0/+1.5%, Max. system voltage: Min. 1000 V, Permissible return current: Min. 15 A, Dimensions (LxWxH in mm): approx. 1719x1140x35, Solar cells: monocrystalline or polycrystalline solar cells, Front cover: low-iron solar glass with anti-reflective coating, Frame: Anodized aluminum, Load capacity: Min. 5400 Pa, Product warranty: 10 years, Module connection box: Min. IP67, Module connector: MC4, Performance warranty: Linear 25 years at 80% minimum power, Certificates: IEC 61215, IEC 61730-1/-2, ISO 9001, ISO 14001, CE
	String or multi-string inverter, AC rated power: min. 25 kVA, Max. input voltage. : min. 1000 V, cos phi : 0.8 inductive 0.8 capacitive, Max. efficiency : min 98.0%, European efficiency. min 97.5%, DC-side module connection via DC plug connector, DC-side disconnection point, String protection from more than 3 strings in parallel, Output voltage: 230 V / 400 V AC, Frequency range 50 Hz, Number of supply phases: 3, Fault current monitoring unit sensitive to all currents, Operating temperature range: -20 °C ... +60°C, Carport mounting. Wall mounting. Protection class (in accordance with IEC 62109-1) : I, Degree of protection (in accordance with IEC 60529): IP65, Overvoltage category (in accordance with IEC 62109-1): AC: III, Cooling, Forced cooling / Variable-speed fans, Display: Graphic display, Data interfaces: RS485/Ethernet/Modbus (depending on system monitoring), Power management in accordance with EEG ("German Renewable Energy Act"), Integrated coupling switch for Mains and system protection in accordance with VDE-AR-N 4105 and 4110, Certificates and approvals: BDEW 2008, CE, IEC 62109-1/-2, VDE 0126-1-1, VDE-AR-N 4105, VDE 0124-100:2012-07, EU Declaration of Conformity 2014/35/EU, 2014/30/EU

Table 8 | Battery Inverter Parameters

DESIGNATION	DESCRIPTION
Battery inverter	Battery-powered inverter with two AC inputs and outputs (e.g. public grid and generator) (one output with automatic switchover from grid to island operation in less than 20 milliseconds, the second output supplies current only when an input voltage is present at one of the inputs), plus one input for 48 V DC voltage with the following specifications: DC input voltage range: 38- 66 V, AC output voltage: 230 V, three-phase operation possible with at least 3 devices or a number of devices divisible by 3 and possibility of connecting inverters in parallel up to a maximum of 4 devices in parallel per phase and 3 phases, total system power max 180 kVA or 2400 A charging current, constant output power at 25° C: 15 kVA, peak power, 25 kVA, max efficiency: min 96%, battery charging current:200 A, constant charging voltage: 57.6 V, battery temperature sensor included, including 3 programmable relays, bus interface for parallel connection and 3-phase operation, remote start/stop, operating temperature : -40 - +65° C, humidity (non-condensing): Max 95%, battery connection, four M8 bolts (2 positive and 2 negative connections), 230 V AC connections, M6 bolts, dimensions approx. 572x488x344, the inverter must contain a battery charger function for lead-acid and lithium-ion batteries, a connection to the battery management system must be integrated), the device must allow grid-parallel and island operation, a connection to DC photovoltaic charge controllers must be possible, including an integrated transfer switch between grid or generator supply and island operation with a maximum switchable current of 2 x 100 A, the system must be capable of remote monitoring and control via the Internet, including the necessary communication and control components.

Table 9 | Charge Controller and Battery Parameters

DESIGNATION	DESCRIPTION
MPPT solar charge controller	MPPT solar charge controller for 48 V, the solar charge controller is connected to a PV grid with a no-load voltage of 80-450 V and is used to charge a 48 V battery, the battery chemistry (lead or lithium-ion) must be supported, the charge controller must be monitored and remotely controlled via the Internet, the charge controller must be equipped with a Can-Bus connection, communication is via Ethernet, battery voltage: 48 V, Nominal charging current: 200 A, Max. charging power: 11.5 kW at 57.6 V, Constant charging voltage: 57.6 V, Programmable output voltage range: 36-62 V, Charging algorithm: multi-level adaptive, Battery temperature sensor included, Max. charging power: 57 kW at 57.6 V, Min. efficiency: 96%, Max. charging power: 57.6 kW at 57.6 V, Battery temperature sensor included. Min. efficiency: 96%, PV voltage voltage: 48 V, starting voltage: 120 V, MPPT voltage range: 80-450 V, Number of MPP trackers: 4, Max. PV operating input current per MPP tracker: 18 A, Max. PV short-circuit current per MPP tracker: 20 A, Max. PV power per MPP tracker: 7.2 kWp, Parallel synchronized operation with up to 25 units via Can-Bus, 1 programmable relay, Reverse polarity protection of PV system, Output short-circuit protection, Overtemperature protection, Operating temperature range: -40 - +60° C, Humidity: max 95%, Dimensions (HxWxD) approx. 487x434x146 mm.
Battery storage system	B3:D7e storage battery system with 15.4 kWh and 48 V battery voltage, usable capacity: 15.36 kWh, max. output current: 250 A, peak output current: 375 A, 10s, dimensions (HxWxD) approx.: 500x575x650 mm, nominal voltage: 51.2 V, voltage range: 40-59 V, ambient temperature range: -10° C - 50° C, cell technology: lithium-iron-phosphate, interfaces: CAN/RS485, IP rating: IP20, battery efficiency: >= 95%, parallel connection: max 64 batteries, battery management must be compatible with the proposed battery inverter, including suitable battery distribution.

3.2 Yield Prediction and Amount of CO_2 Avoided

The results presented in this section are those expected from the pre-tender simulation. With the components proposed, it will be possible to produce around 168,126 kWh of electrical energy per year, giving a specific annual yield of 1,608.16 kWh/kWp and a coefficient of performance[11] of 83.64%.

Let Alpha (α) be the sum of direct own consumption and consumption covered by the battery system. The own consumption rate is the ratio of Alpha and the total production of the solar

[11] Ratio between the energy production actually delivered by the PV system and the expected power based on solar radiation and panel surface area.

system. The solar coverage rate, on the other hand, is the ratio of alpha to the building's total consumption. According to predictions, this will be 61.2%, while the proportion of own consumption will be 78.8%.

The detailed simulation results are shown in Table 10. This shows that approximately 146,269 kg of CO_2 could be avoided per year.

Table 10 | Estimated Annual Production, Energy Performance Coefficients and Emission Reductions

PARAMETERS	*VALUE*	*UNIT*
PV Installation		
PV generator power	104.52	kWp
Specific annual yield	1,608.16	kWh/kWp
Plant coefficient of performance (PR)	83.64	%
Yield reduction due to shading	0.8	%/ a
Energy from PV generator (AC grid)	168,126	kWh/ a
Direct own consumption	76,521	kWh/ a
Battery charging	56,014	kWh/ a
Energy resold	35,591	kWh/ a
Own consumption share	78.8	%
CO_2 emissions avoided	146,269	kg/ a
Consumers		
Total building consumption	200.000	kWh/ a
Stand-by consumption (UPS)	42	kWh/ a
Covered by the grid	77,591	kWh/ a
Self-sufficiency	61.2	%

3.3 System Installation

3.3.1 Technical Analysis and PV Data Essentials

Following the call for tenders, one bid was submitted. Bonergie SARL[12] was the sole bidder and was commissioned to build the photovoltaic system. The system components listed in Table 11 were included in the bid submitted.

Table 11 | Excerpt from Bonergie's "Specifications" Form.

SYSTEM COMPONENT	MANUFACTURER AND TYPE
Photovoltaic module	Trina Solar 450 Wp
Inverter	Fronius ECO 27 kW
Data logger	Victron Cerbo GX
Three-phase sensor	Fronius Smartmeter TS 5kA
Battery inverter	Victron Quattra 15 kVA
MPPT solar controller	Victron Smartsolar RS 450/200
Storage system	BYD 15,4 kWh

A PV*SOL simulation and wiring diagram were included in the offer. Figure 7 illustrates the connection diagram between the PV modules and the corresponding inverters. For example, four strings of 17 modules were connected to the "Fronius ECO 27 kW" inverter. The simulation was carried out with a 20 kW inverter from the same manufacturer: this is also connected to four strings, although only 11 modules are connected in series.

[12] Bonergie SARL: a Senegal-based solar firm provides solar products tailored for productive purposes, contributing to income generation for customers.

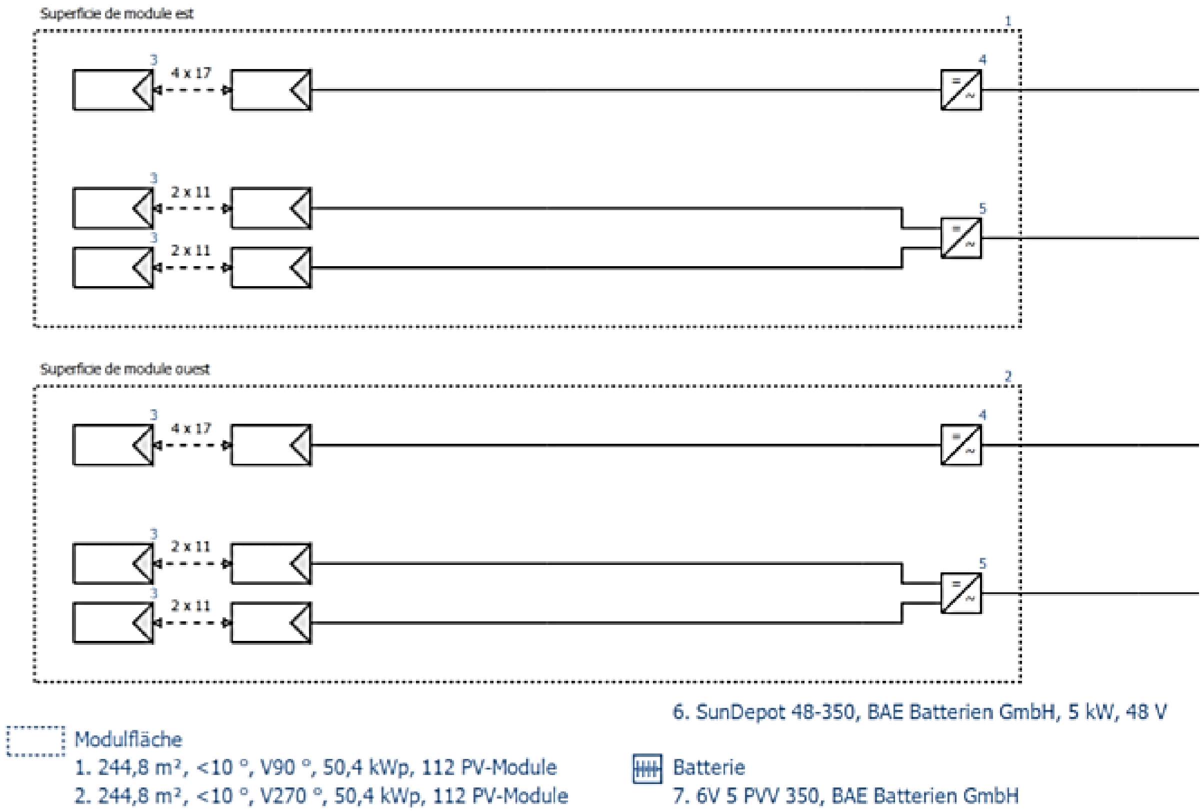

Figure 7 | PV System Interconnection Diagram, (© IfaS)

As we saw above, the configuration of strings connected to an inverter depends on its parameters (voltage, current, power, etc.). The total voltage and power of the modules connected to the inverter at certain temperatures must not exceed those of the inverter, and the maximum power of the MPP must not be outside the limits of the inverter**Fehler! Textmarke nicht definiert.**. To verify this and other requirements, please consult the data sheets for modules and inverters.

Table 12 shows the characteristics of the modules used, and Table 9 lists the inverter specifications.

Table 12 | Excerpt from the Module Data Sheet[13]

ELECTRICAL DATA (STC)	VALUE	UNIT
Rated power (P_{MPP})	450	[W]
Rated voltage (U_{MPP})	41	[V]
Rated current (I_{MPP})	10.98	[V]
No-load voltage (U_{OC})	49.4	[V]
Short-circuit current (I_{SC})	11.53	[A]
Temperature coefficients		
Temperature coefficient I_{SC} α (I_{SC})	0.04	[%/K]
Temperature coefficient UOC β (U_{OC})	-0.26	[%/K]
Temperature coefficient PMPP γ (P_{MPP})	-0.36	[%/K]
Electrical voltages (temperature-dependent)		
No-load voltage U_{OC} (-10°C)	54	[V]
Nominal voltage U_{MPP} (-10°C)	46	[V]
Nominal voltage U_{MPP} (25°C)	41	[V]
Nominal voltage U_{MPP} (70°C)	34	[V]

[13] Data from Bonergie: https://bonergie.com

Table 13 | Extract from Inverter Data Sheet and Comparison of Parameters

PARAMTER	***INVERTER DESIGNATION***	
	FRONIUS 27.0-3-S	**FRONIUS 20.0-3-M**
Max. AC power $P_{WR,Max}$ [W]	27000	20000
Maximum AC voltage $U_{WR,Max}$ [V]	580	600
Maximum current $I_{WR,Max}$ [A]	47.7	27
Minimum nominal voltage $U_{WR,Min,MPP}$ [V]	580	420
Maximum nominal voltage $U_{WR,Max,MPP}$ [V]	850	800
Number of strings (s)	4	2
Number of modules per string (n)	17	11
Comparison result		
$n.s.P_{MPP} <= P_{WR,Max}$	30,600	9,900
$s.I_{SC} <= I_{WR,Max}$	46.12	23.06
$n.U_{OC}(-10°C) <= U_{IN,Max}$	916.22	592.85
$U_{WR,Min,MPP} <= n.U_{MPP} <= U_{WR,Max,MPP}$	697	451
$U_{WR,Min,MPP} <= n.U_{MPP}(70°C) <= U_{WR,Max,MPP}$	584.09	377.94
$U_{WR,Min,MPP} <= n.U_{MPP}(-10°C) <= U_{WR,Max,MPP}$	784.82	507.83

Table 13 shows that the recommendations have been followed when wiring the PV modules. Noting that the "FRONIUS 27.0-3-S" inverter's maximum power and no-load voltage have been exceeded (orange). In principle, this overshoot is not good, but the value is still within the tolerance range. In the worst case, the ratio between PV power and inverter power must not exceed the factor 1.25**Fehler! Textmarke nicht definiert.**. As far as no-load voltage is concerned, the assessment is not relevant at this stage, as there is no negative voltage in Senegal. Similarly, the PV cell temperature of 70°C is generally not reached if the modules are well ventilated during installation**Fehler! Textmarke nicht definiert.**, so failure to reach the minimum UMPP at 70°C is not a problem.

3.3.2 PV Plant at UGB

In the second half of 2023, Bonergie has successfully installed the PV plant for UGB-Building A (see Figure 8). during this period, many students from the Interuniversity Master in Renewable Energies program[14] Master Interuniversitaire en Energies Renouvelables (MIER) had participated in the installation of a state-of-the-art photovoltaic (PV) plant at the heart of our academic hub (see. Figure 9).

The purpose of integrating students in this activity is learning how the PV plant seamlessly integrates with the university's existing infrastructure. Furthermore, the reason is not only generating clean energy but also cultivates a new generation of environmentally conscious and skilled individuals.

Figure 8 | PV Plant Installed in Building A at UGB, (© IfaS)

[14] MIER: Master Interuniversitaire en Energies Renouvelables-Interuniversity Master in Renewable Energies. https://www.ugb.sn/sat/index.php/90-sat/143-master-energies-renouvelables

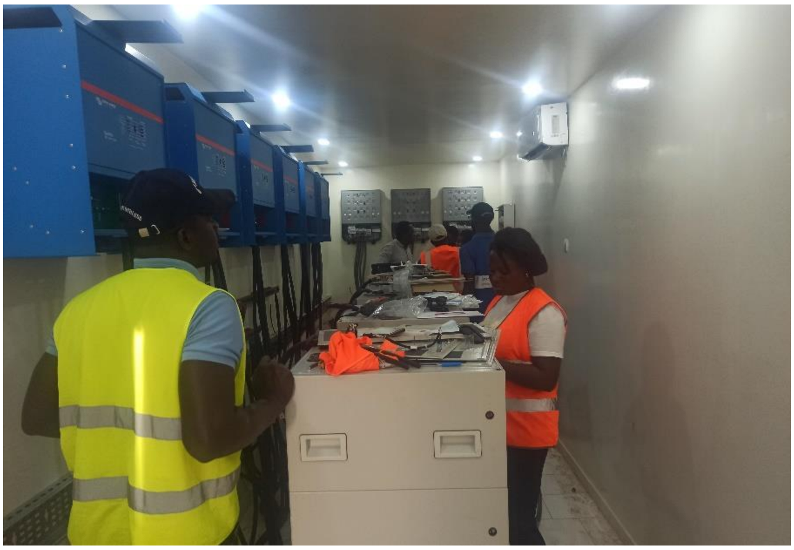

Figure 9 | Technical Chamber of PV Plant at UGB with the Participation of Students and Technicians, (© IfaS)

3.4 Monitoring and Results

The installation of the photovoltaic (PV) system at UGB has been underway, but numerous delays have affected the timeline. Despite these challenges, the monitoring phase is currently in progress. The implementation of the PV system is a crucial step towards sustainable energy solutions for UGB, and diligent efforts are being made to address any setbacks encountered during the installation process. Once completed, the system will contribute to the university's commitment to environmentally friendly energy practices.

3.4.1 Monitoring

When monitoring a photovoltaic system, a visual assessment is essential. This enables any errors to be spotted in good time. The first presentation in Figure 10 shows a typical example of such errors, which may not be observable at the UGB, since the system has just been built. More information later on will help to highlight the shortcomings of this figure:

1. Features high-voltage AC power cables, which are exposed to the open air. A storm could have caused this.
2. Shows an inverter whose display has failed, making it impossible to read the current output. Only remote monitoring can remedy this situation. In the following, the emphasis will be on remote supervision.
3. Shows the dust on the solar modules. That's why, as part of the LoSENS project, water will be piped to the roof of building A, so that the modules can be cleaned if necessary.
4. Gives an overview of the cables connected with cable ties, as required by construction standards.

Figure 10 | Tour of a Photovoltaic System at the Birkenfeld Environmental Campus in Germany, (© IfaS)

3.4.2 Online Monitoring

3.4.3 Comparison of Results with Other Sources

Various software packages, including PV*SOL, are available to simulate photovoltaic installations.

In this work, the results obtained with PV*SOL are compared with data from Solargis and Renewables ninja. After simulation with PV*SOL, the result is that 224 PV modules will be installed at UGB. This corresponds to a total module area of 489.68 m^2. As the PV module tracks do not contain any PV cells, we have subtracted around 0.5 cm from the original length. On this assumption, the total surface area is 486.17 m^2. This figure is multiplied by the specific yield of 2,120 kWh/(m^2*a)[15] , the module yield and the system utilization rate of 78% (LACH-HEB et al., 2021). The result is an annual yield of 162,268 kWh. Another way of calculating the yield would

[15] Global Solar Atlas: https://globalsolaratlas.info

be to take the product of the installed power (100.8 kWp) and the specific yield of 1,753 kWh/(kWp*a) [45]. The resulting yield is 176,702 kWh. The average of these two yields was taken as a result with Solargis.

The results of the three above-mentioned sources are compared in **Fehler! Verweisquelle konnte nicht gefunden werden.**

Table 14 | Simulation Results with PV*SOL and Renewables Ninja and Calculation Results with Solargis Data

DESIGNATION	***VALUE***	***UNIT***
Solargis		
Yield_1 (with installed power)	176,702	KWh/ a
Yield_2 (with total area)	208,248	kWh/ a
Yield correction (area with cells only)	206,754	kWh/ a
System utilization rate	78.0	%
Yield_2 with system utilization rate	161,268	kWh/ a
Average yield	**168,985**	kWh/ a
Specific yield	**1,753**	kWh/(kWp. a)
PV*SOL		
Annual Yield	**168,126**	kWh/ a
Specific Annual yield	**1,608**	kWh/(kWp. a)
Renewables Ninja		
Annual yield	**189,280**	kWh/ a

NOTE: In Table 15, the influencing parameters are listed alongside the results, to help understand the differences. The "Comments" column deserves particular attention here.

Table 15 | Comparison of Results for PV*SOL, Solargis and Renewables Ninja.

SOURCE	DESIGNATION	VALUE	UNIT	PARAMETER	VALUE	UNIT	COMMENT
PV*SOL	Annual yield	168,126	kWh	Radiation on module surfaces	1.942	kWh/m²	Any losses (due to dust, wiring, weather, etc.) are taken into account here. The modules are tilted and receive only part of the total solar radiation.
	Specific yield	1,608.16	kWh/kWp	Module inclination	10	°	
Solargis	Annual yield	168,985	kWh	Specific efficiency	1.753	kWh/(kWp*a)	The degree of loading of the system components influences the yield. Solargis does not take this into account. It is also partly calculated with maximum horizontal irradiation and maximum module efficiency. Module inclination and orientation are neglected. As a result, this yield would be higher, even though the plant utilization rate used is only 78%.
	Specific yield	1,753	kWh/kWp	Horizontal radiation	2.120	kWh/(m²*a)	
Renewables ninja	Annual yield	189,280	kWh/a	Horizontal radiation	1.963	kWh/(m²*a)	The southern orientation of the solar modules, as set during the simulation with Renewables ninja, is advantageous, as the system is illuminated throughout the day and therefore provides a higher yield. A south-east or north-west orientation, as at UGB, was not possible. Losses were also neglected in this simulation.
				Module inclination	10	°	
				Losses	0	%	

Despite the differences, the results for Solargis and PV*SOL are very comparable. Although the results with Renewables ninja seem rather high, they are almost identical to the others (PV*SOL and Solargis). Yields with Renewables ninja are 13% higher than with PV*SOL. The technical losses (plant utilization rate) of a PV plant vary between 10% and 20% (Fraunhofer ISE, 2023). The 13% calculated is within this range, and can be attributed to the plant utilization rate neglected by Renewables ninja.

3.5 Economic Evaluation

The parameters and assumptions in Table 16 are used to calculate the economic performance indicators. To determine the operating costs (maintenance, operating and insurance costs) of a PV plant, it is recommended to assume an annual amount of 1.5% of the investment and a useful life of 20 years**Fehler! Textmarke nicht definiert.**. In this work, it is assumed that annual operating costs amount to 2% of the investment. Insurance costs are shown separately, at 1% of CAPEX, and electricity costs are taken from an invoice from Université Gaston Berger. It is also assumed that these costs increase by 1% per year, as shown in Table 16.

Table 16 | Parameters for Costing.

PARAMETER	*VALUE AND UNIT*	*UNIT*
Operating cost rates	2.00	%
Increase in operating costs	1.00	%
Insurance rates	1.00	%
Increase in insurance costs	1.00	%
Electricity price increase	1.00	%
Price kWh	0.21	€
Annual kWh production	168,126	kWh/a
Amount of kWh production in 20 years	3,362,520	kWh

Table 16 shows the annual composition of cash flow over the useful life of the PV plant. For reasons of clarity, some years have been masked out. Thanks to the PV system to be built at UGB, each kilowatt-hour produced will cost €0.147. The internal rate of return associated with CAPEX and OPEX is 8%.

Table 17 | Economic Analysis for A 100 kWp System with Batteries

PARAMETER	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	YEAR 6	YEAR 7	YEAR 8
PV System Cost	**-151,000**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Cost of the storage system	**-120,898**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Cost of Ownership	-5,438	-5,492	-5,547	-5,603	-6,376	-6,440	-6,505	-6,570
Insurance	-2,719	-2,746	-2,774	-2,801	-3,188	-3,220	-3,252	-3,285
Charged Costs	-280,055	-288,293	-296,614	-305,018	-422,234	-431,894	-441,651	-451,506
Feed-in tariff	0	0	0	0	0	0	0	0
Power Generation	160,816	160,012	159,212	158,416	148,422	147,680	146,942	146,207
Savings	34,555	34,726	34,552	34,379	32,210	32,049	31,889	31,730
Annual Cashflows	**-245,500**	**26,487**	**26,231**	**25,975**	**22,646**	**22,389**	**22,132**	**21,875**
Cumulated Cashflows	-245,500	-219,013	-192,782	-166,807	147,573	169,962	192,095	213,970
LCOE	**0.147 €/kWh**							

Figure 11 shows the accumulated cashflow and the plant's amortization period. The latter is approximately 10.5 years.

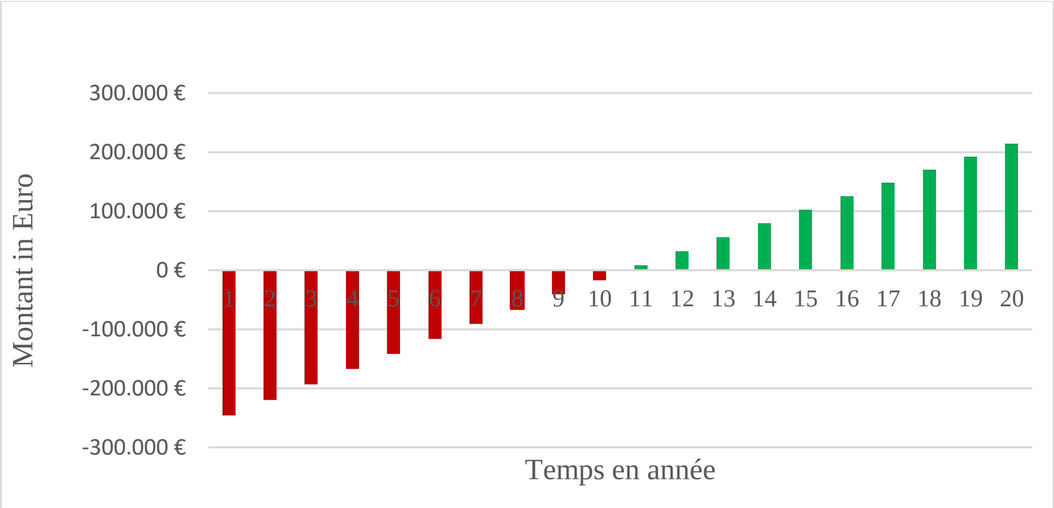

Figure 11 | Cash Flow from A PV System with Batteries Over the Useful Life, (© IfaS)

The payback time for the system without storage with 100% self-consumption will be around 5.5 years, while the LCOE (cost price of a kilowatt-hour) would be reduced to €0.082. Such a system will be more profitable, with an internal rate of return of 22.96%.

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5 Appendix

Appendix I | Table of Battery Inverter Parameters

SHORT TEXT	DESCRIPTION
Battery inverter	Supply and installation: Battery inverter with two AC inputs and outputs (e.g. public grid and generator) (one output with automatic switchover from grid to island operation in less than 20 milliseconds, the second output supplies current only when an input voltage is present at one of the inputs), plus one input for 48 V DC voltage with the following specifications: DC input voltage range: 38- 66 V, AC output voltage: 230 V, three-phase operation possible with at least 3 devices or a number of devices divisible by 3, and possibility of connecting inverters in parallel up to a maximum of 4 devices in parallel per phase and 3 phases, total system power max 180 kVA or 2400 A load current, constant output power at 25 °C: 15 kVA, peak power, 25 kVA, max efficiency: min 96%, battery charging current: 200 A, constant charging voltage: 57.6 V, battery temperature sensor included, including 3 programmable relays, bus interface for parallel connection and 3-phase operation, remote on/off, operating temperature : -40 - +65° C, humidity (non-condensing): Max 95%, battery connection, four M8 bolts (2 positive and 2 negative connections), 230 V AC connections, M6 bolts, dimensions approx. 572x488x344. The inverter must include a battery charger function for lead-acid and lithium-ion batteries, a connection to the battery management system must be integrated), the device must enable grid-parallel and island operation, connection of photovoltaic DC charge controllers must be possible, including an integrated transfer switch between grid or generator supply and island operation with a maximum switchable current of 2 x 100 A, the system must be capable of remote monitoring and control via the Internet, including the necessary communication and control components. Delivered, connected ready for use and commissioned.

Appendix II | Table of Charge Controller and Battery Parameters.

SHORT TEXT	DESCRIPTION
MPPT solar charge controller	MPPT solar charge controller for 48 V, the solar charge controller is connected to a PV grid with a no-load voltage of 80-450 V and is used to charge a 48 V battery, the battery chemistry (lead or lithium-ion) must be supported, the charge controller must be monitored and remotely controlled via the Internet, the charge controller must be equipped with a Can-Bus connection, communication is via Ethernet, battery voltage: 48 V, Nominal charging current: 200 A, Max. charging power: 11.5 kW at 57.6 V, Constant charging voltage: 57.6 V, Programmable output voltage range: 36-62 V, Charging algorithm: multi-level adaptive, Battery temperature sensor included, Max. charging power: 57 kW at 57.6 V, Min. efficiency: 96%, Max. charging power: 57.6 kW at 57.6 V, Battery temperature sensor included. Min. efficiency: 96%, PV voltage voltage: 48 V, Starting voltage: 120 V, MPPT voltage range: 80-450 V, Number of MPP trackers: 4, Max. PV operating input current per MPP tracker: 18 A, Max. PV short-circuit current per MPP tracker: 20 A, Max. PV power per MPP tracker: 7.2 kWp, Parallel synchronized operation with up to 25 units via Can-Bus, 1 programmable relay, Reverse polarity protection of PV system, Output short-circuit protection, Overtemperature protection, Operating temperature range: -40 - +60 °C, Humidity: max 95%, Dimensions (HxWxD) approx. 487x434x146 mm. Delivered, connected ready for use and commissioned.
Battery storage system	Storage battery system with 15.4 kWh and 48 V battery voltage, usable capacity: 15.36 kWh, max. output current: 250 A, peak output current: 375 A, 10s, dimensions (HxWxD) approx.: 500x575x650 mm, nominal voltage: 51.2 V, voltage range: 40-59 V, ambient temperature range: -10 °C – 50 °C, cell technology: lithium-iron-phosphate, interfaces: CAN/RS485, IP rating: IP20, battery efficiency: >= 95%, parallel connection: max 64 batteries, battery management must be compatible with the proposed battery inverter, including suitable battery distribution. Delivered, connected ready for use and commissioned.

Appendix III | Table of Module and Inverter Parameters[16].

SHORT TEXT	DESCRIPTION
Module >=335 Wp	Photovoltaic modules with the following minimum requirements: STC power: Min. 395 Wp, Module efficiency: Min. 19.9%, Power tolerance (STC): -0/+1.5%, Max. system voltage: Min. 1000 V, Permissible return current: Min. 15 A, Dimensions (LxWxH in mm): approx. 1719x1140x35, Solar cells: monocrystalline or polycrystalline solar cells, Front cover: low-iron solar glass with anti-reflective coating, Frame: Anodized aluminum, Load capacity: Min. 5400 Pa, Product warranty: 10 years, Module connection box: Min. IP67, Module connector: MC4, Performance warranty: Linear 25 years at 80% minimum power, Certificates: IEC 61215, IEC 61730-1/-2, ISO 9001, ISO 14001, CE Flash data must be supplied for each module. Supply and installation of integrated bypass diodes
Inverter 25 kVA	Inverter with remote data readout with the following specifications: String or multi-string inverter, AC rated power: min. 25 kVA, Max. input voltage: min. 1000 V, cos phi: 0.8 inductive. 0.8 capacitive, Max. efficiency: min 98.0%, European efficiency. min 97.5%, DC-side module connection via DC plug connector, DC-side disconnection point, String protection from more than 3 strings in parallel, Output voltage: 230 V / 400 V AC, Frequency range 50 Hz, Number of supply phases: 3, Fault current monitoring unit sensitive to all currents, Operating temperature range: -20 °C ... +60 °C, Carport mounting. Wall mounting. Protection class (in accordance with IEC 62109-1) : I, Degree of protection (in accordance with IEC 60529): IP65, Overvoltage category (in accordance with IEC 62109-1): AC: III, Cooling, Forced cooling / Variable-speed fans, Display: Graphic display, Data interfaces: RS485/Ethernet/Modbus (depending on system monitoring), Power management in accordance with EEG ("German Renewable Energy Act"), Integrated coupling switch for Mains and system protection in accordance with VDE-AR-N 4105 and 4110, Certificates and approvals: BDEW 2008, CE, IEC 62109-1/-2, VDE 0126-1-1, VDE-AR-N 4105, VDE 0124-100:2012-07, EU Declaration of Conformity 2014/35/EU,

[16] KLE Energie GmbH

Appendix IV | Table of Battery Inverter Parameters

SHORT TEXT	DESCRIPTION
Battery inverter	Supply and installation: Battery inverter with two AC inputs and outputs (e.g. public grid and generator) (one output with automatic switchover from grid to island operation in less than 20 milliseconds, the second output supplies current only when an input voltage is present at one of the inputs), plus one input for 48 V DC voltage with the following specifications: DC input voltage range: 38- 66 V, AC output voltage: 230 V, three-phase operation possible with at least 3 devices or a number of devices divisible by 3 and possibility of connecting inverters in parallel up to a maximum of 4 devices in parallel per phase and 3 phases, total system power max 180 kVA or 2400 A load current, constant output power at 25 °C: 15 kVA, peak power, 25 kVA, max efficiency: min 96%, battery charging current: 200 A, constant charging voltage: 57.6 V, battery temperature sensor included, including 3 programmable relays, bus interface for parallel connection and three-phase operation, remote on/off, operating temperature : -40 - +65 °C, humidity (non-condensing): Max 95%, battery connection, four M8 bolts (2 positive and 2 negative connections), 230 V AC connections, M6 bolts, dimensions approx. 572x488x344, the inverter must contain a battery charger function for lead-acid and lithium-ion batteries, a connection to the battery management system must be integrated), the device must allow grid-parallel and island operation, a connection to DC photovoltaic charge controllers must be possible, including an integrated transfer switch between grid or generator supply and island operation with a maximum switchable current of 2 x 100 A, the system must be capable of remote monitoring and control via the Internet, including the necessary communication and control components. Delivered, connected ready for use and commissioned.

Appendix V | Table of Charge Controller and Battery Parameters.

SHORT TEXT	DESCRIPTION
MPPT solar charge controller	MPPT solar charge controller for 48 V, the solar charge controller is connected to a PV grid with a no-load voltage of 80-450 V and is used to charge a 48 V battery, the battery chemistry (lead or lithium-ion) must be supported, the charge controller must be monitored and remotely controlled via the Internet, the charge controller must be equipped with a Can-Bus connection, communication is via Ethernet, battery voltage: 48 V, Nominal charging current: 200 A, Max. charging power: 11.5 kW at 57.6 V, Constant charging voltage: 57.6 V, Programmable output voltage range: 36-62 V, Charging algorithm: multi-level adaptive, Battery temperature sensor included, Max. charging power: 57 kW at 57.6 V, Min. efficiency: 96%, Max. charging power: 57.6 kW at 57.6 V, Battery temperature sensor included. Min. efficiency: 96%, PV voltage voltage: 48 V, Starting voltage: 120 V, MPPT voltage range: 80-450 V, Number of MPP trackers: 4, Max. PV operating input current per MPP tracker: 18 A, Max. PV short-circuit current per MPP tracker: 20 A, Max. PV power per MPP tracker: 7.2 kWp, Parallel synchronized operation with up to 25 units via Can-Bus, 1 programmable relay, Reverse polarity protection of PV system, Output short-circuit protection, Overtemperature protection, Operating temperature range: -40 - +60 °C, Humidity: max 95%, Dimensions (HxWxD) approx. 487x434x146 mm. Delivered, connected ready for use and commissioned.
Battery storage system	Storage battery system with 15.4 kWh and 48 V battery voltage, usable capacity: 15.36 kWh, max. output current: 250 A, peak output current: 375 A, 10s, dimensions (HxWxD) approx.: 500x575x650 mm, nominal voltage: 51.2 V, voltage range: 40-59 V, ambient temperature range: -10 °C – 50 °C, cell technology: lithium-iron-phosphate, interfaces: CAN/RS485, IP rating: IP20, battery efficiency: >= 95%, parallel connection: max 64 batteries, battery management must be compatible with the proposed battery inverter, including suitable battery distribution. Delivered, connected ready for use and commissioned.

Appendix VI | Other Site Pictures of PV Installation